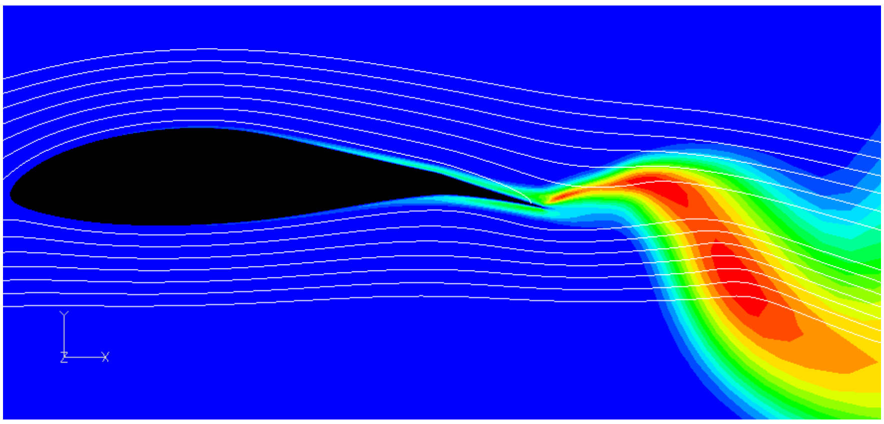
INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research,
Development and Deployment of Wind Turbine Systems
Task 11

56th IEA Topical Expert Meeting

THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR BLADES

Aluquerque, USA, May 2008
Organised by: Sandia National Labs



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IEA RD&D Wind Task 11

Topical Expert Meeting #56

THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR BLADES

February, 2008

INTRODUCTORY NOTE

IEA TOPICAL EXPERT MEETING #56

ON

THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR BLADES

To be held at Sandia National Laboratories, May 8-9, 2008

Dale Berg, Sandia National Laboratories

THE TOPIC

In his introductory note for the initial IEA topical expert meeting on this topic in December 2006, Gijs van Kuik summarized the evolution of wind turbine control to the current commercial state-of-the-art; a system that utilizes variable rotor speed and the simultaneous full-span blade pitch (commonly referred to as collective blade pitch) of all blades to optimize energy yield and control the loads on the turbine. The resulting increase in energy capture, combined with the hardware cost reductions due to lower loads on the blades and attenuation of the drive train torque excursions, have more than offset the additional costs associated with the new control capability.

Numerous studies have concluded that adding independent full-span blade pitch to the collective blade pitch of the existing control system has the potential to significantly reduce the current level of fatigue loads, especially the periodic loading due to yaw and wind shear. These lower fatigue loads will result in lighter (and cheaper) blades, drive train and nacelle. The benefits of independent blade pitch control will not come without cost, however: it will involve much higher duty factors for blade pitch bearings and motors, leading to increases in the cost of those components. Nevertheless, the addition of independent blade pitch will probably be the next major change in wind turbine control.

The stochastic nature of the wind gives rise to fatigue loads that vary over a wide range of time and length scales. While pitch control can alleviate loads that are fairly uniform along a blade and that vary with a time scale of a few seconds, it cannot alleviate loads that vary with position on the blade and that change with a time scale of milliseconds. Control of these distributed, rapidly changing loads requires distributed sensors to determine the local loads, distributed intelligence to decode the sensor information, and distributed small, fast-acting control devices to modify the local aerodynamic characteristics of the blade and alleviate the loads.

As Gijs mentioned in his earlier note, the development of the technology required to accomplish this load mitigation, often referred to as 'smart structures' or 'smart technology', is an interdisciplinary development par excellence. It requires a joint effort in the following disciplines (and probably several others):

- Aerodynamics of airfoils with distributed control elements
  Several options are available for the adjustment of lift and drag; flaps, micro-tabs, plasma actuators and boundary layer suction or blowing are some of the control devices available.
- Actuators
  The activation of the aerodynamic devices must be fast and reliable and consume minimal power. While well known options such as piezo-electric elements and shape-memory alloys offer several attractive characteristics, significant challenges must be addressed to develop cost-effective

actuators that last for 20 years.

- Sensors
  The sensors to determine the local blade loads must be fast-response, inexpensive, durable and accurate. Fiber-optic cable incorporating fiber Bragg gratings is one promising option.
- Control
  The control algorithms for this type of control are not yet available. Fast, real-time load identification algorithms, allowing application of predictive control techniques, is a challenging task. Self-learning and adaptive algorithms will be used to design a fault-tolerant controller incorporating failsafe technology to protect the turbine if the active control malfunctions or fails. This will require a major development effort.
- Communication and power supply
  These links to and between the sensors, control logic devices and actuators must be highly reliable and highly resistant to lightning strikes.
- Blade material and construction
  The active devices should ideally be embedded in the blade material, avoiding slots or cavities in the blade surface that could lead to contamination of the inner structure. This requirement may lead to new methods of blade construction, such as the use of spars and ribs, but the cost of the blade must remain low.
- Blade design and analysis tools
  The tools available today are limited to analysis of common methods of blade construction utilizing centralized control. More flexible design tools must be developed to accommodate innovative blade construction and distributed control options.

Recent experimental work at Risø and TU Delft has verified analytical work showing that active devices can indeed have a dramatic effect on the loads experienced by and dynamic response of a blade subjected to unsteady wind loading. However, much work remains to be done before this technology is ready for deployment on commercial wind turbines.

OBJECTIVES OF THE MEETING

The objectives of the meeting are to report and discuss progress of R&D on all of the above mentioned topics. Since this area of research is relatively new (for wind turbines), many challenges and solutions are still to be discussed and tested. It is expected that the expert meeting will result in new and challenging directions in R&D due to the discussions between experts of different origin.

EXPECTED OUTCOMES

Compilation of the most recent information on the topic. Input to define IEA Wind R&D's future possible role in this topic

TENTATIVE AGENDA

Participants in the meeting are expected to discuss the subject in detail and give a short presentation relevant to the topic. Presentation length is usually around 15 minutes, depending on the number of presentations in the meeting.

The tentative agenda of this two-day meeting covers the following items:

1 Introduction by host
2 Introduction by Operating Agent, Recognition of Participants
3 Collect titles of presentations and compile presentation order
4 Presentation of Introductory Note
5 Individual presentations
6 Discussion
7 Summary of meeting

INTENDED AUDIENCE

The national members will invite potential participants from research institutions, utilities, manufacturers and any other organizations willing to participate in the meeting by means of presenting proposals, studies, achievements, lessons learned, and others. This means then that the symposia will be wide open, considering that it is only the second time that this subject will be discussed within the framework of the IEA Wind RD&D.

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IEA Topical Expert Meeting 56 on

The Application of Smart Structures for Large Wind Turbine Rotor Blades

Dale E. Berg
Sandia National Laboratories
Albuquerque, NM USA

8-9 May, 2008

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Objectives

- **Significantly reduce blade loads**
  - **vary with position on blade**
  - **vary with time scale of a few secondsIncrease energy capture**
- **Use local flow control**
- **Utilize distributed**
  - **sensors**
  - **intelligence**
  - **small, fast-acting control devices**
- **Modify local aerodynamics of the blade**
- **Maintain reliability**
- **Minimize additional cost**

Local Load Control

- Idea of distributed load control is not new
- Early work showed that controls could lower fatigue loads

Why Revisit Local Load Control?

- Size has increased
- Large size means loads vary quickly & dramatically along blade
- Active pitch control can only control “average” load on blade
- Passive load control cannot respond to local load variations
- Fatigue loads can drive the lifetime of all turbine components

What Benefits do We Expect to Gain?

- **Lower fatigue loads**
- **Increased energy capture**
- **Actively suppress vibration (certain modes)**
- **Control noise?**
- **To fully realize the potential benefits, may need to design a machine from scratch that integrates local flow control**

Key Areas of Concern

- **Aerodynamics of airfoils with distributed control elements**
  - **Multiple devices available to adjust lift & drag**
  - **Need CFD(?) tools to determine device performance characteristics**
  - **Need aero/CFD(?) tools to determine control effects on entire system**
- **Actuators**
  - **Control device must be deployed, retracted, moved**
  - **Needs:**
    - low power
    - dependable
    - replaceable
    - cheap
    - immune to lightning
    - small?
  - **Bi-stable or multi-stable devices are interesting**

Key Areas of Concern

- **Sensors**
  - **Many types are available today**
  - **Needs**
    - cheap
    - reliable
    - accurate
    - durable (last 20 years)
    - replacable
  - **What do we need to measure?**
    - loads
    - state of flow
    - deflection
    - acceleration
    - ????

Sandia National Laboratories

Key Areas of Concern

- **Controls**
  - **Major development required**
  - **Needs:**
    - fast
    - real-time load identification
    - fault tolerant
    - improved energy capture
    - site and condition adaptive (self learning)
    - failsafe
    - predictive?
    - multiple time scales, multiple impact levels

Sandia National Laboratories

Key Areas of Concern

- **Communications and power supply**
  - **Not usually considered high tech problem**
  - **Needs:**
    - highly reliable
    - immune to lightning
    - avoid wires?
- **New blade materials and construction**
  - **Incorporate control devices/actuators/sensors**
  - **Preserve integrity of blade interior**
  - **Replaceable control elements**

Sandia National Laboratories

Key Areas of Concern

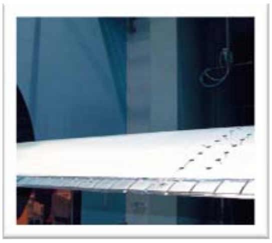
- **Blade design and analysis tools**
  - **Increase capability**
  - **Accommodate**
    - innovative blade construction
    - new materials
    - distributed control

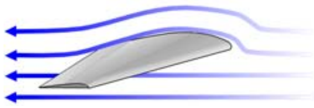
Sandia National Laboratories

Development Process Stages

- Research
  - analysis
  - laboratory testing
- Proof of Concept
  - small/medium scale prototype testing
- Commercial Viability
  - large scale prototype field testing
- Commercial application

Latest results and future activities at Risø DTU within trailing edge flaps



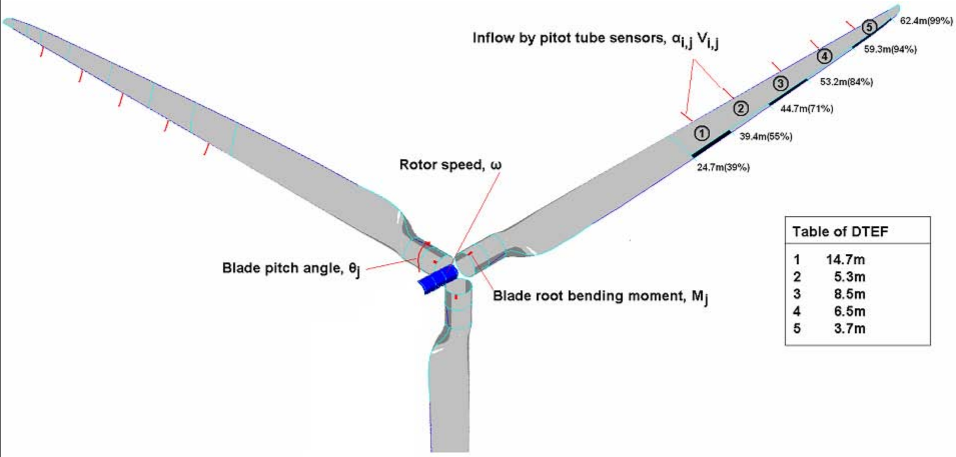
Thomas Buhl Senior Scientist Risø-DTU
Peter B. Andersen, Mac Gaunaa, Christian Bak, Helge Aa. Madsen
Frederik Zahle, Joachim Heinz, Leonardo Bergami, Li Na, Andreas Fisher

Activities on trailing edge flap at Risø DTU:

- Stability
- CFD
- New Concepts (rubber/piezo)
- Advanced controls
- Wind tunnel test
- Full scale tests
- Sensor design

Introduction (1:2)

Sensors and DTEG positions

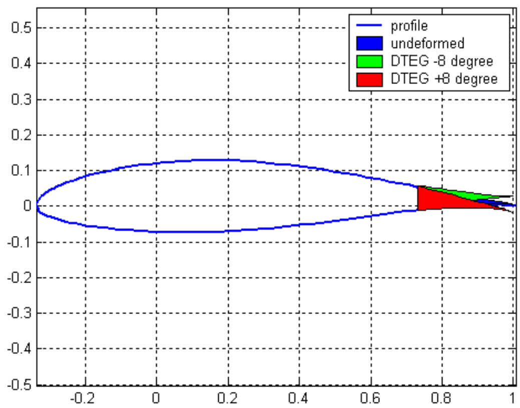


From the ADAPWING2 project funded by Danish Research Council

Introduction (2:2)

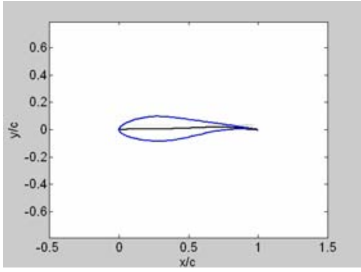
DTEG Property assumptions:

- 10% of chord
- +/- 8 degree deflection possible
- from +/-8 to -/+8 in simulated “dt” (=0.01s)
- no effects of hysteresis
- no overshoot or other dynamics
- max $\Delta CL(\alpha,\beta=8deg) = 0.29$
- min $\Delta CL(\alpha,\beta=-8deg) = -0.29$



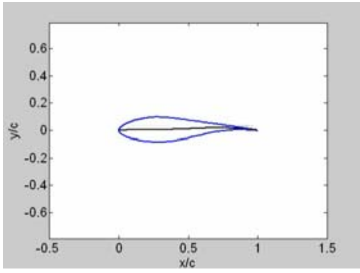
Stability

Classical flutter



142 m/s

"Control flutter"



90 m/s

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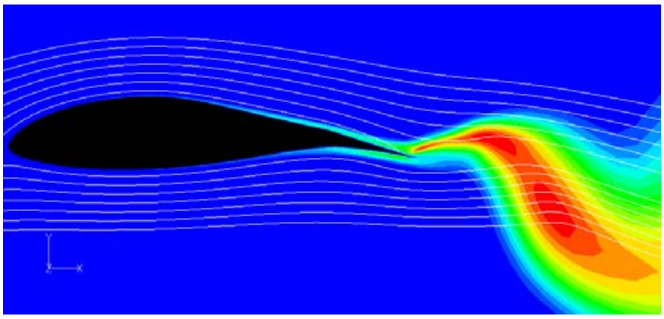
CFD



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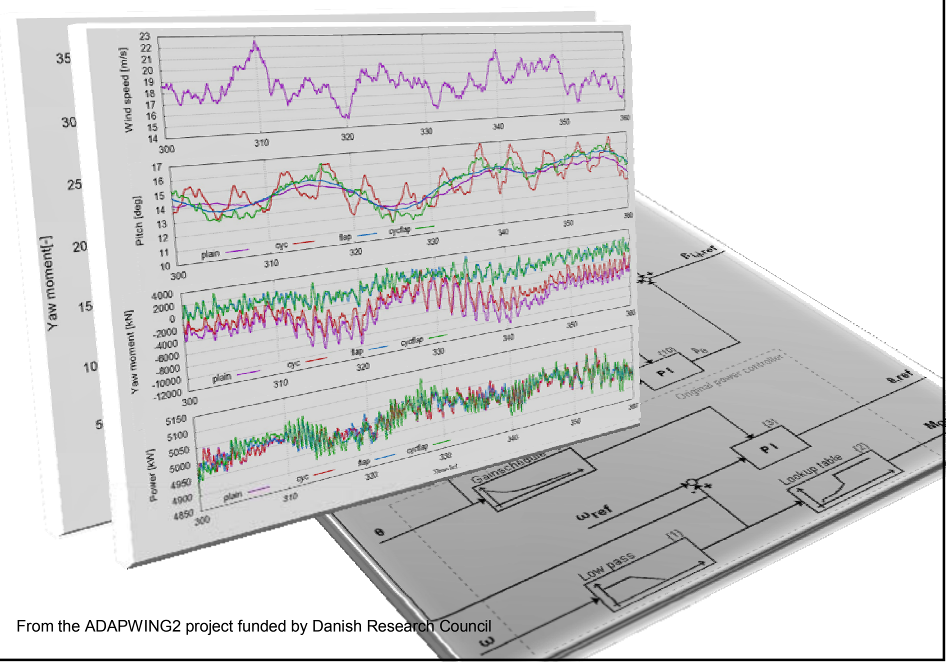
Advanced Controllers



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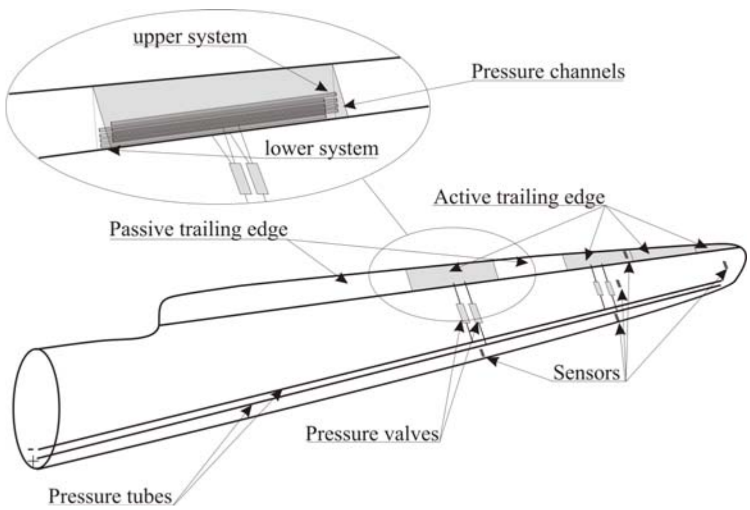
New concepts



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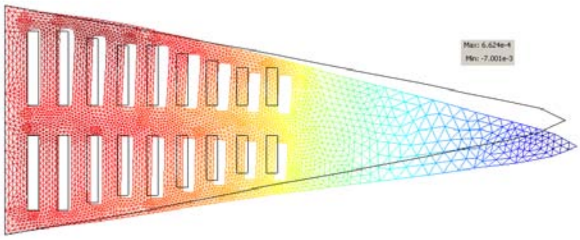
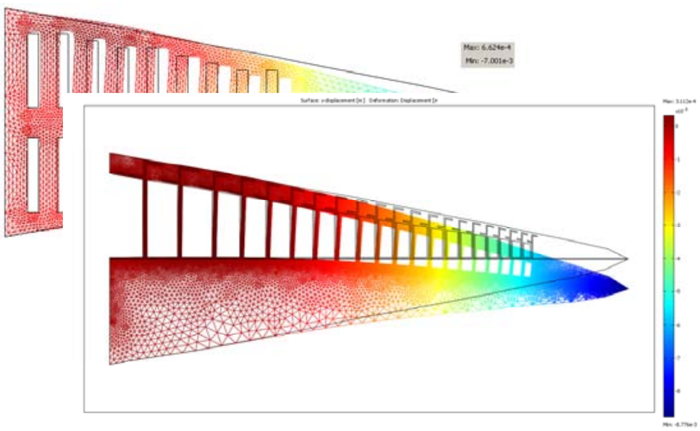
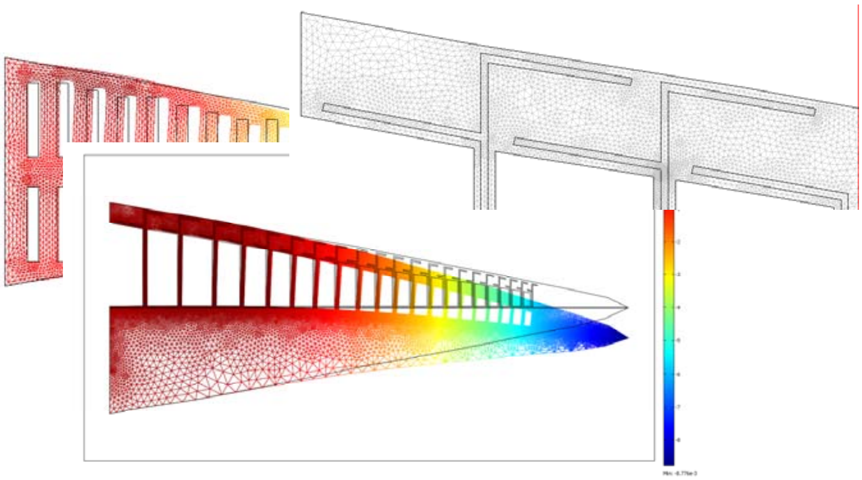
New concepts



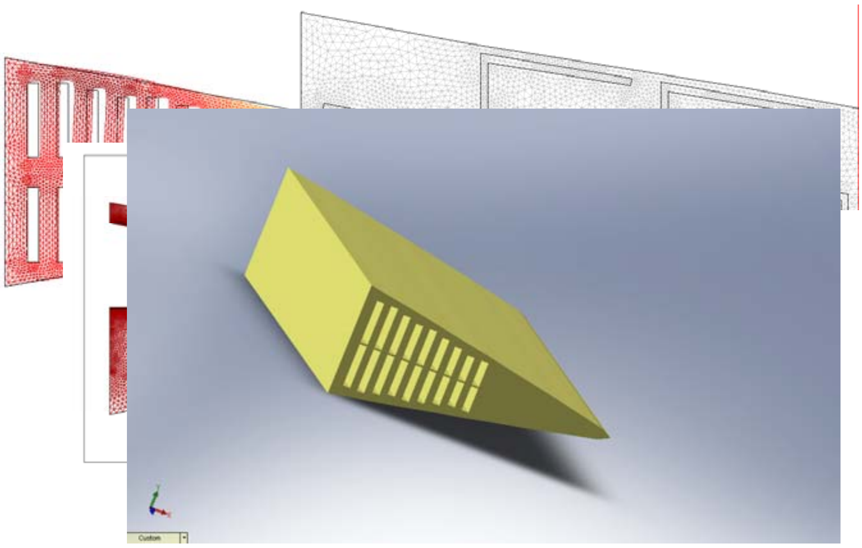
New concepts



New concepts



New concepts



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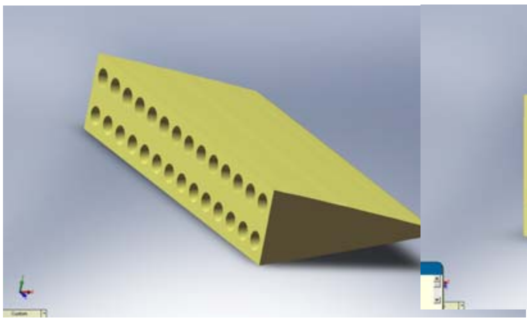
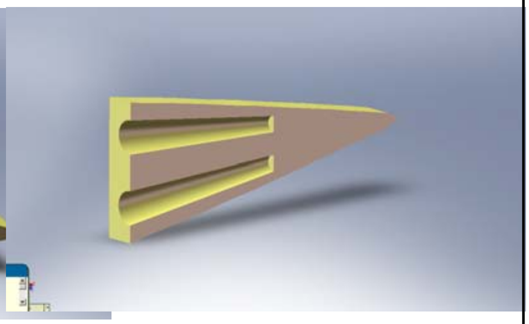
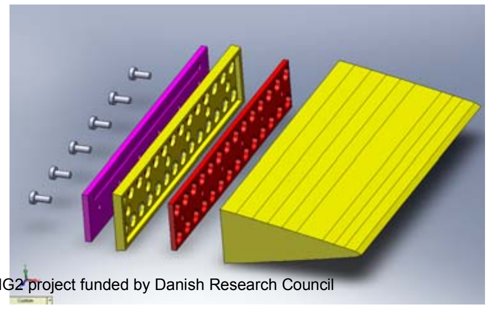
New concepts







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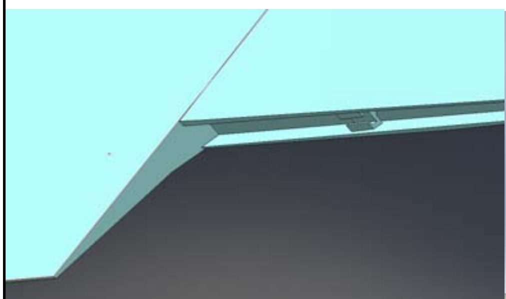
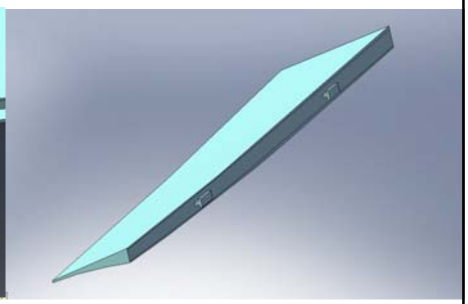
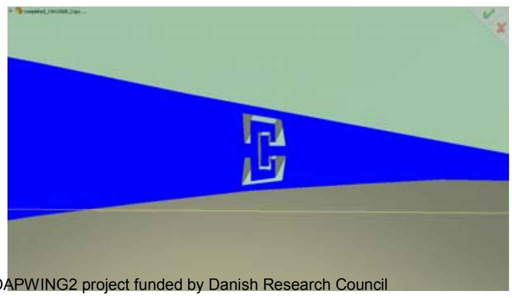
New concepts







From the ADAPWING2 project funded by Danish Research Council

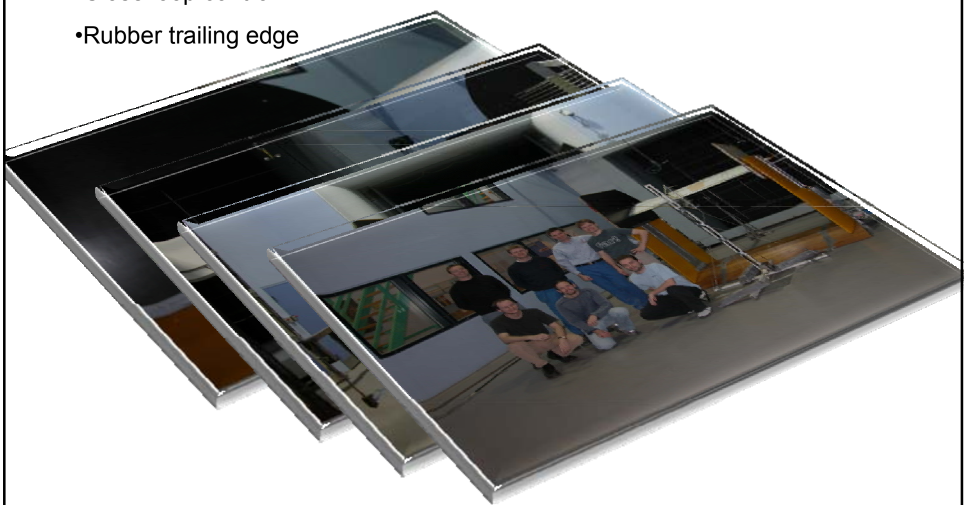
Wind tunnel tests

From the ADAPWING2 project funded by Danish Research Council

Wind tunnel tests

Planned for the near future:

- Close loop control
- Rubber trailing edge



Full scale tests

After summer 2008 full instrumentation of the test turbine V27

Beginning of 2009 measurement campaign for 3 month on the V27

May 2009 apply trailing edge flaps to existing blades

Summer 2009 measurement campaign with trailing edge flaps

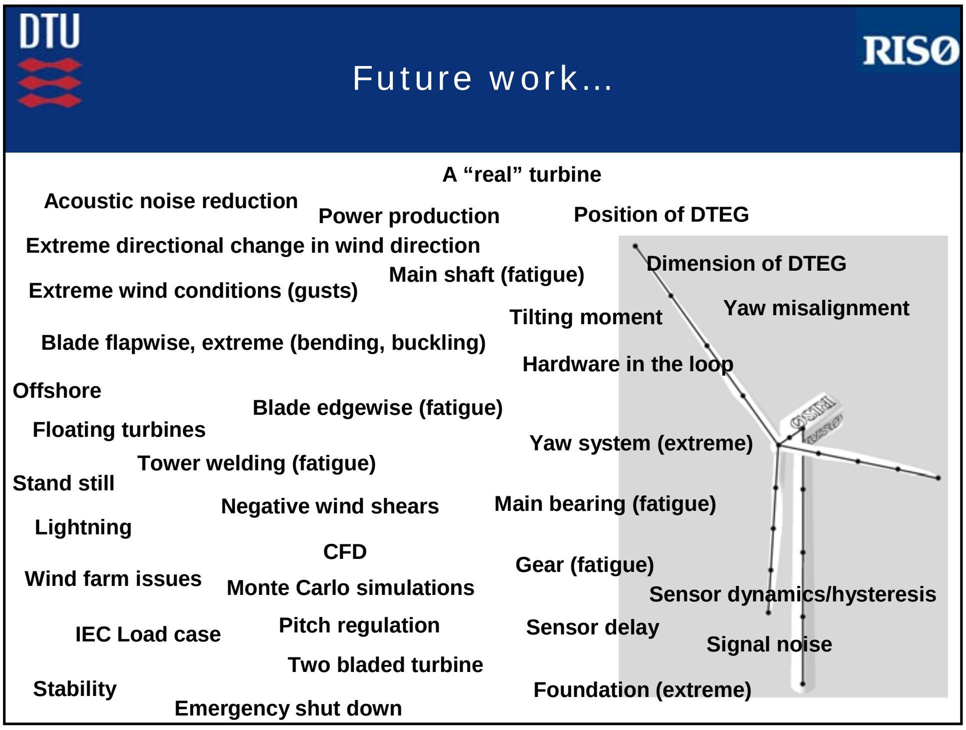
Sensor design

Development of Pitot tubes:

Measurement campaign with Pitot tubes

Analysis of data

development of “new” Pitot tubes


DTU
RISØ
Future work…
A “real” turbine
Acoustic noise reduction
Power production
Position of DTEG
Extreme directional change in wind direction
Dimension of DTEG
Main shaft (fatigue)
Extreme wind conditions (gusts)
Tilting moment
Yaw misalignment
Blade flapwise, extreme (bending, buckling)
Hardware in the loop
Offshore
Blade edgewise (fatigue)
Floating turbines
Yaw system (extreme)
Tower welding (fatigue)
Stand still
Negative wind shears
Main bearing (fatigue)
Lightning
CFD
Gear (fatigue)
Wind farm issues
Monte Carlo simulations
Sensor dynamics/hysteresis
IEC Load case
Pitch regulation
Sensor delay
Signal noise
Two bladed turbine
Stability
Foundation (extreme)
Emergency shut down

ATEF – Feasibility study for optimising Danish upwind turbine technology

IEA Workshop 8-9 May 2008

Dick Veldkamp
Vestas R&D Global Research

Contents

- Objectives of ATEF (Adaptive Trailing Edge Flaps) project
- Background, results already obtained
- Results from a test on Tilt Yaw control
- Future plans

An apology

- ATEF work presented here was done by others (DTU/Risoe, TU Delft)
- No Vestas ATEF results so far, only plans
- Results of Tilt Yaw control are confidential

Objectives

- Reduce loads on turbine and blades by 'micromanaging' aerodynamic loads (wind gradients, turbulence). This should:
  - Make larger rotor diameters possible
  - Reduce material consumption
  - Reduce turbine distance in parks
  - Decrease loads on challenging sites (complex terrain)
- Increase energy capture with given rotor diameter by aerodynamic enhancement

Background - Helicopters

Background:

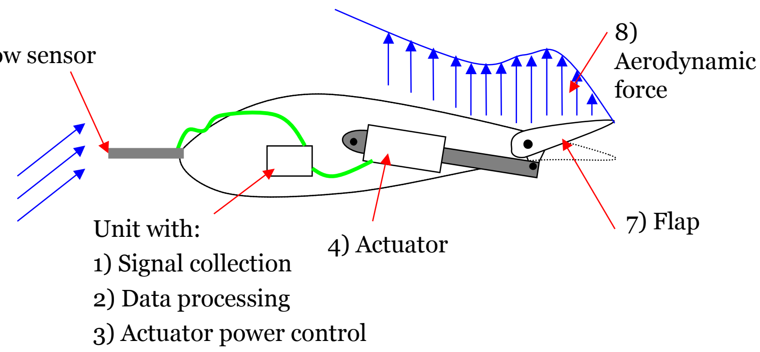
A team led by The Boeing Company [NYSE: BA] has successfully used advanced materials in the design, development and testing of a revolutionary new helicopter rotor that could benefit all rotorcraft.

The Smart Material Actuated Rotor Technology (SMART) system offers an **80 percent vibration reduction**, a jet-smooth ride and other benefits. It employs existing materials to drive on-blade trailing edge flaps to reduce vibration and noise and improve aerodynamic performance. Whirl tower testing was conducted by Boeing at its Mesa, Ariz., rotorcraft facility

Below: Eurocopters first test flight in 2005 with trailing edge flaps implemented with piezo actuators (ADASYS)

The aim of this project is to develop a similar concept that could be used for wind turbine systems

Principle using known technology



Background 1: Results from Adaptive Trailing Edge Flap at Risø over the past 3 years

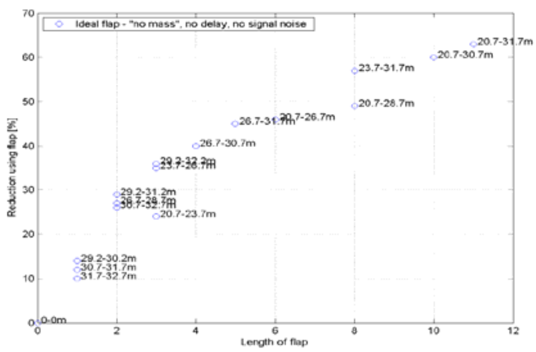
Results available:

- Wind tunnel test confirm flap functionality and profile data
- Practical experience with angle-of-attack measurements in full scale
- Aero-elastic simulations of a V90/2 MW showing improvement
- But the devil is in the details…

Pictures: A single Piezo element and below implementation on the wind tunnel model

Design optimization

- Flaps are to control loads and modal shape, so there is an optimum configuration
  - No. of flaps per blade
  - Length, size of each flap
- Also to be considered is blade structural integrity, mechanical design, reliability and serviceability

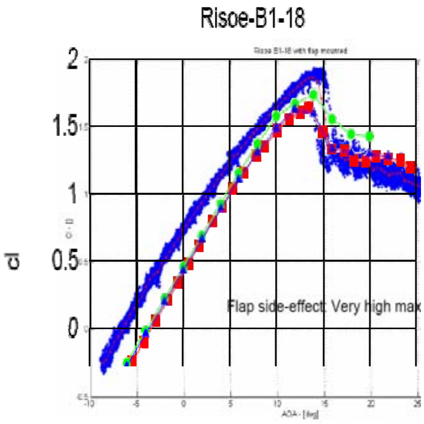


Increased energy capture?

- A flap in it self allows for large increase of lift, thus also opens possibility to enhance performance

- $\Delta C_L = 0.04\ \alpha_{TEF}$ (+/- 0.5)
- $\Delta C_D = 0$

- Find the right balance between increase AEP and loads



Background: Work by TU Delft

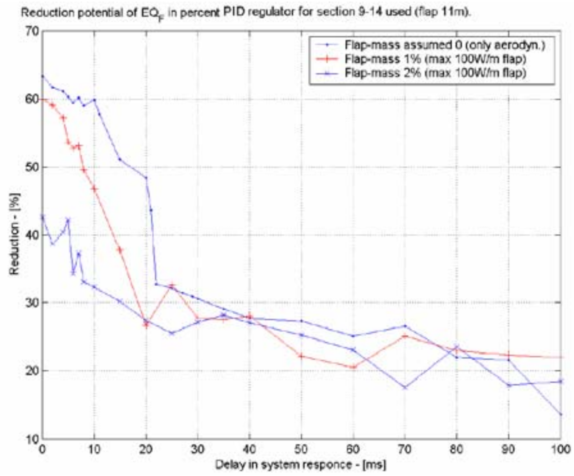
- Control

- Proof of concept in wind tunnel (2D, piece of blade)

- Movie (courtesy of Jan Willem van Wingerde, TU Delft, 3ME)

Why ATEF, why not just turn the whole blade ?

- Reaction time is critical; response speed high
- The modal shape can be controlled (i.e. local flaps)
- In complex wind schemes the blade cuts through large speed differences.



Use of Adaptive Trailing Edge Flaps: status

- ATEFs are promising
- Practical issues will be the problem
- Must be better than existing technology, especially individual pitch control (IPC)
- How good is IPC?

Test of Tilt Yaw control (IPC)

- 10 V90-3MW turbines in complex terrain (Portugal)
- Switch TYC on and off on the same turbine
- Compare loads and power output

- Acknowledgement: the research was done by Erik Miranda, Michael Krabbe and Søren Kjær Nielsen

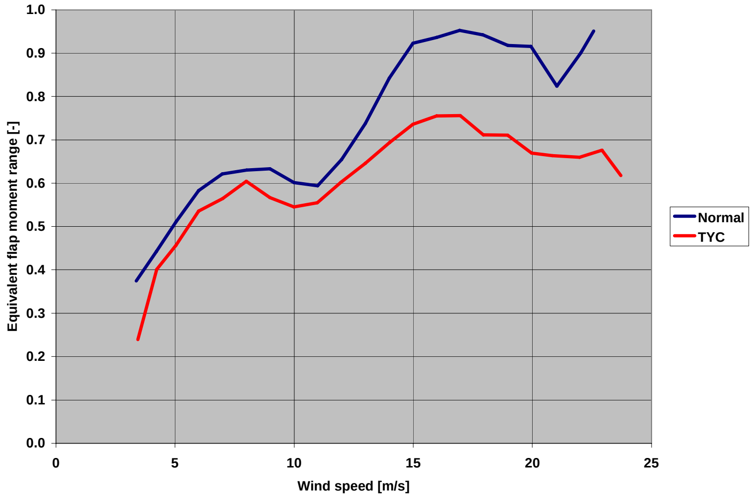
Vestas

Principle of Tilt Yaw control

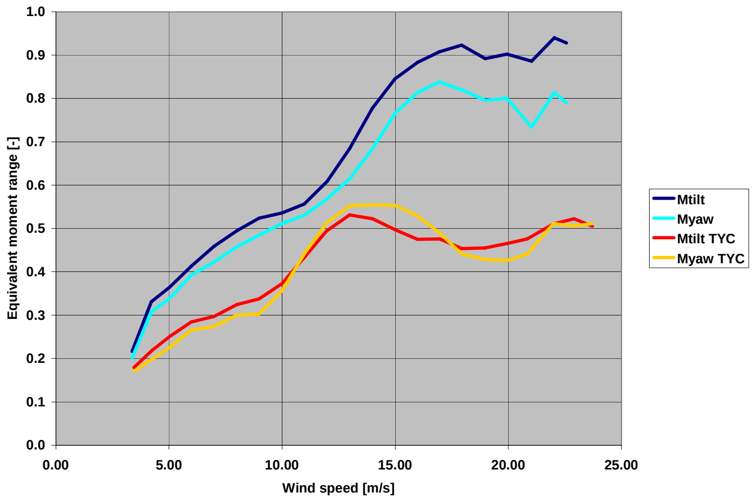
- Minimise tilt and yaw moment variation
  - Measure blade root flap bending moments
  - Apply transformation to fixed frame, find tilt and yaw moments
  - Calculate required control action
  - Apply back transformation to blades, find desired pitch angle
  - Pitch the blades (on top of normal pitching)

Vestas

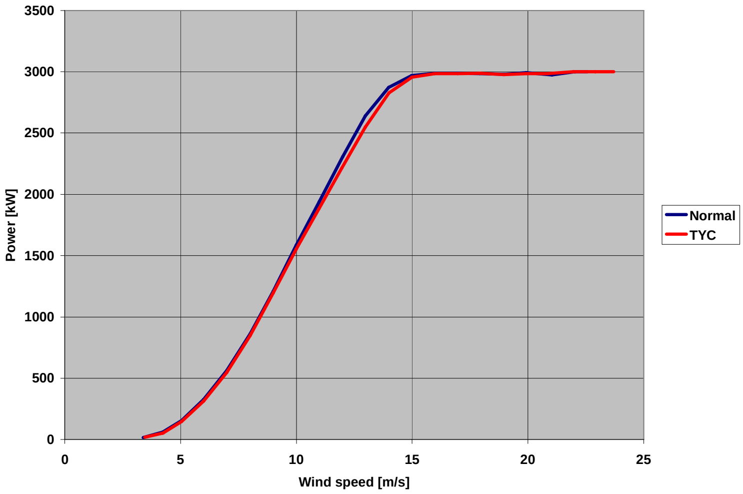
Equivalent blade root flap range



Equivalent tilt and yaw moment



Power curve



Energy loss

- Slightly reduced power curve: 1-2% production loss (AEP, IEC II wind regime, Uavg = 8.5 m/s)
  - Confirms Vestas calculations
  - Matthew Lackner (TU Delft) also ca 1% loss

- 0.5 – 1% loss due to extra pitching, the rest due to non-optimal blade setting

Tilt Yaw Control: status

- Tilt yaw control works; test correspond well to calculations (not shown here)
- Reduction blade root flap moment ranges by ca 20%
- Small (but non negligible) power loss
- “Proven technology”
- Challenge: make ATEF improve on this!

ATEF project with DTU-Risø

- 3½ year program with DTU-Risø
  - DKK 30,000,000 (EUR 4,000,000)
  - 10 persons 3 years
  - Financial contribution from Danish Advanced Technology Fund 50%

Activities (1)

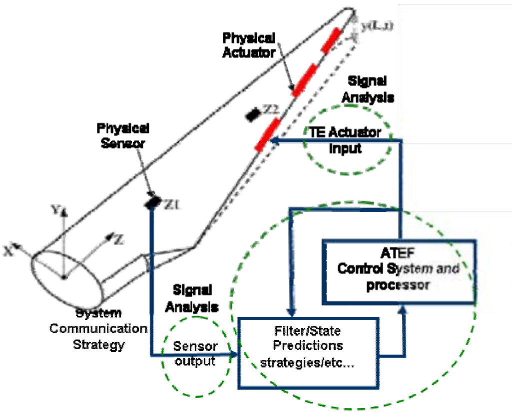
- WP1: Aero-elastic calculations in HAWC and Flex5 on existing Vestas turbines.
  - What can ideally be achieved?
  - Analysis control, frequency problems
- WP2: Development of advanced CFD
  - The whole works: dynamic sensor and flap response in 3D-flow with elastic deformations
- WP3 :system design
  - Development of control strategies
  - Development of sensors and actuators for real operational conditions
  - Detail testing

Activities (2)

- **WP4: Hardware test on V47**
  - Instrumentation of turbine
  - Test of sensors
  - Test of flaps
  - Wind tunnel test with controller
  - Preparation of a blade
  - Test of control strategies
- **WP5: prototype test on MW size turbine**

Realisation elements on a WTG:

- Sensor(s)
  - Flow sensor (angle of attack, local head)
  - Load sensor (strain)
  - Movement sensor (tip/hub)
- Flap implementation
  - Actuator and electro-mechanics
- Flap aerodynamic response
- Algorithms for control
  - Local control
  - Integration with overall WTG TYC
- Power supply for actuator/sensor
- Communication
  - Sensor-CPU-actuator and
  - Interface to WTG controllers
- ATEF Control and Processing unit
- Blade and flap, structural integration
- Service and reliability



Conclusion

- ATEF looks very promising, but getting something to work reliably is a challenge
- ATEF must be an improvement on IPC
- In all cases our knowledge of rotor aerodynamics and control will be greatly enhanced.
- Next time: a more substantial presentation!

Thank you for your attention!

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FOCUS

Integrated design of smart structures

N.P. Duineveld

Sandia National Laboratories

May 8-9th, 2008

Knowledge Centre WMC
Wind turbine Materials and Constructions

TUDelft ECN

Introduction

FOCUS, an integrated wind turbine design tool

Novem project 224.720.9535: FOCUS version 4
Novem project 224.720.9635: Windows-95 interface for FOCUS4

FOCUS 5: Internal development

SenterNovem project: 2020-04-11-10-003: FOCUS 6 (2004-2008)

INNWIND - Innovation in Wind Energy (2006-2011)

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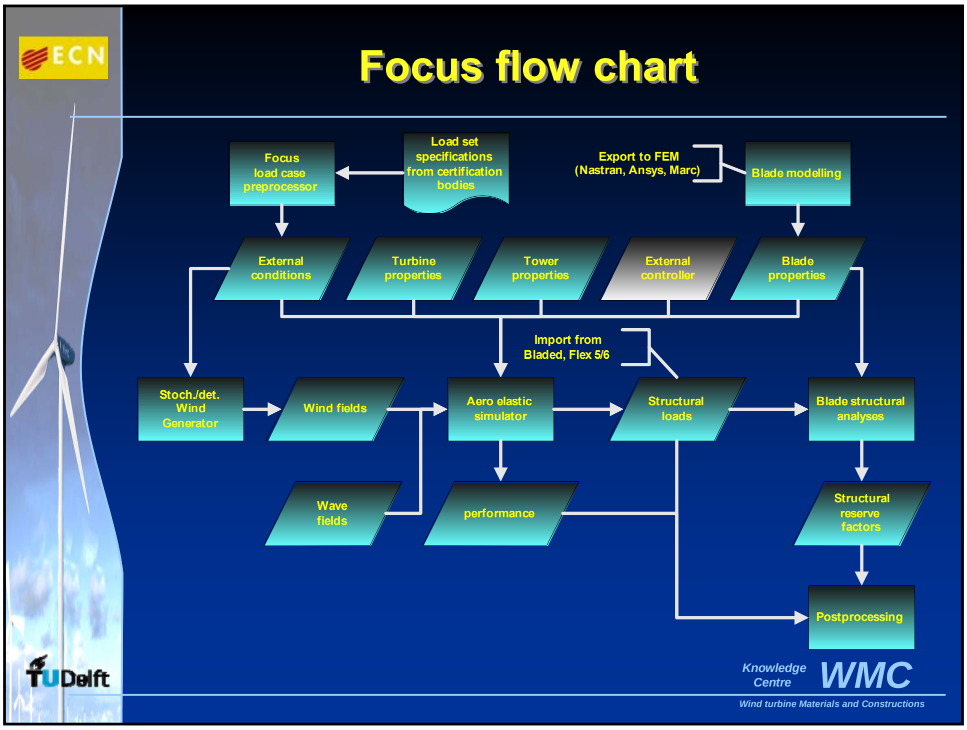
TUDelft ECN


ECN
Focus flow chart
Focus load case preprocessor
Load set specifications from certification bodies
Export to FEM (Nastran, Ansys, Marc)
Blade modelling
External conditions
Turbine properties
Tower properties
External controller
Blade properties
Import from Bladed, Flex 5/6
Stoch./det. Wind Generator
Wind fields
Aero elastic simulator
Structural loads
Blade structural analyses
Wave fields
performance
Structural reserve factors
Postprocessing
TUDelft
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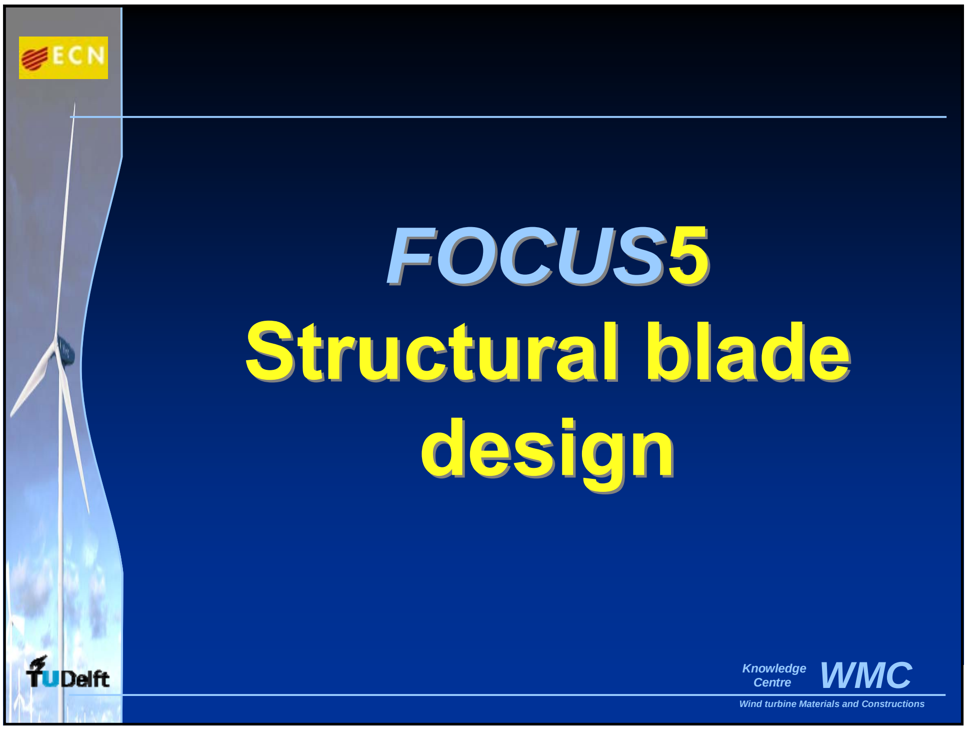
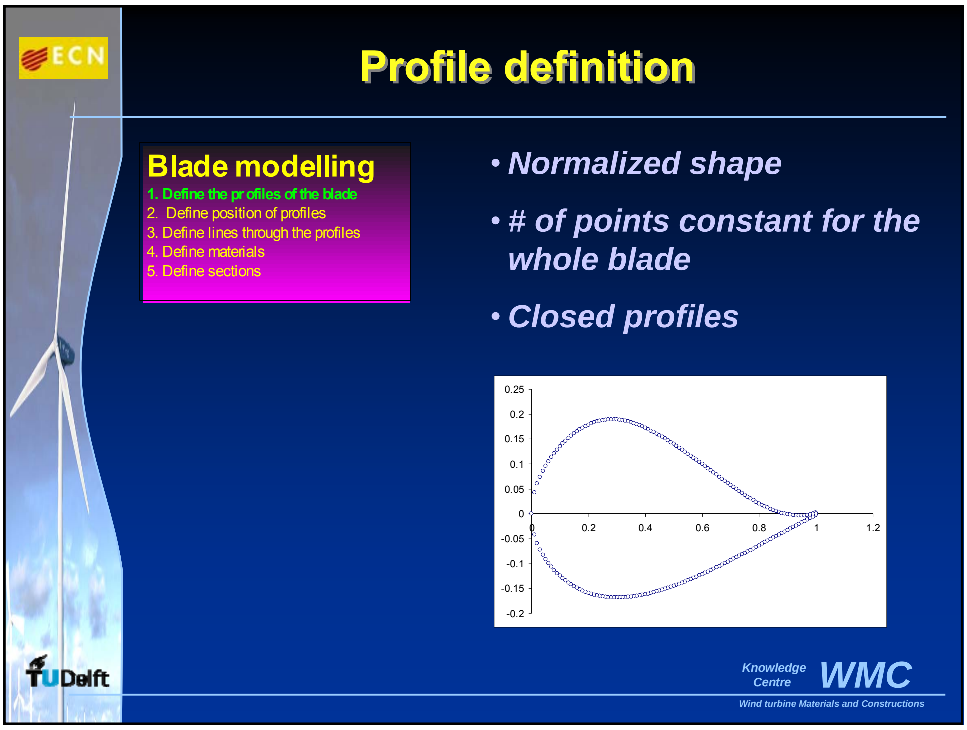
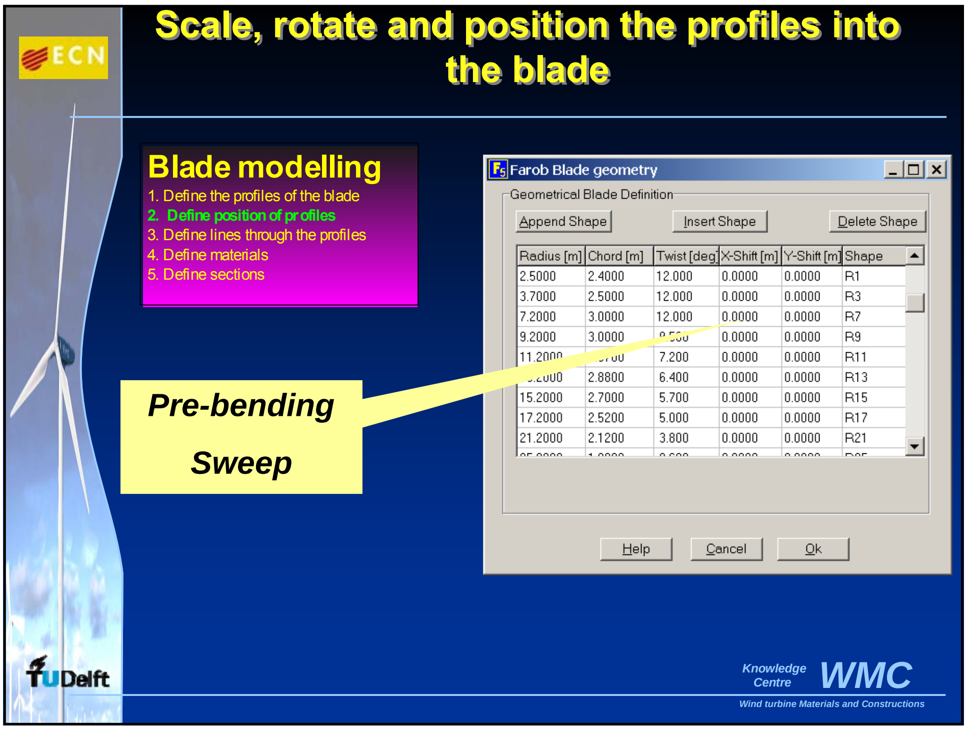
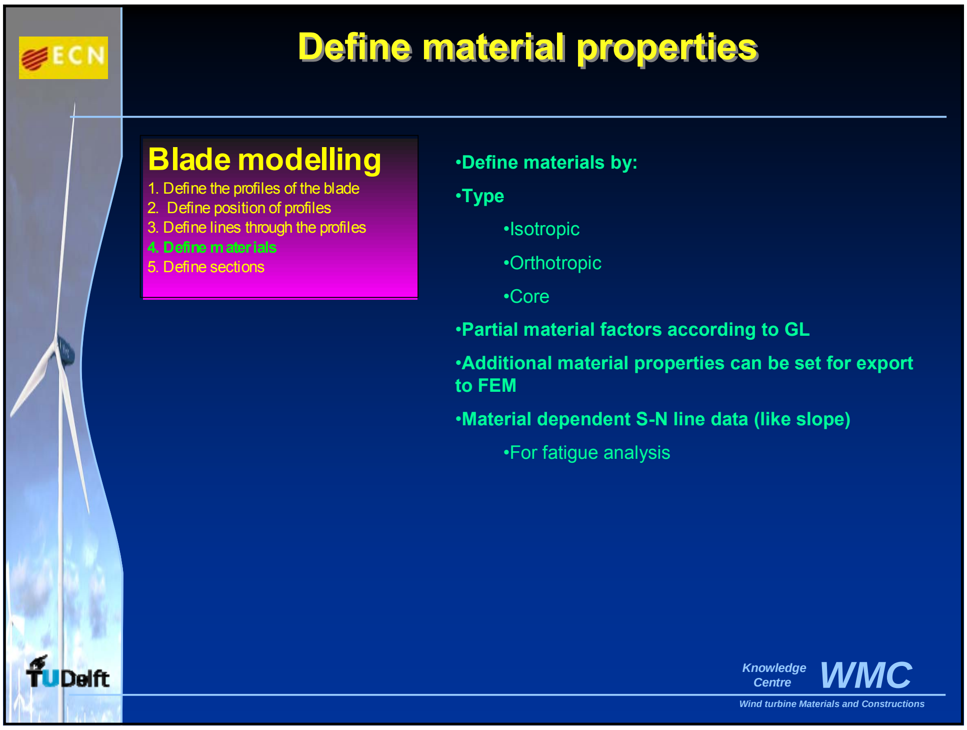

ECN
FOCUS5
Structural blade design
TUDelft
Knowledge Centre
WMC
Wind turbine Materials and Constructions


Profile definition
Blade modelling
1. Define the profiles of the blade
2. Define position of profiles
3. Define lines through the profiles
4. Define materials
5. Define sections
• Normalized shape
• # of points constant for the whole blade
• Closed profiles
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
Knowledge Centre WMC
Wind turbine Materials and Constructions


Scale, rotate and position the profiles into the blade
Blade modelling
1. Define the profiles of the blade
2. Define position of profiles
3. Define lines through the profiles
4. Define materials
5. Define sections
Pre-bending
Sweep
Farob Blade geometry
Geometrical Blade Definition
Append Shape
Insert Shape
Delete Shape
Radius [m] Chord [m] Twist [deg] X-Shift [m] Y-Shift [m] Shape
2.5000 2.4000 12.000 0.0000 0.0000 R1
3.7000 2.5000 12.000 0.0000 0.0000 R3
7.2000 3.0000 12.000 0.0000 0.0000 R7
9.2000 3.0000 0.0000 0.0000 R9
11.2000 7.200 0.0000 0.0000 R11
2.8800 6.400 0.0000 0.0000 R13
15.2000 2.7000 5.700 0.0000 0.0000 R15
17.2000 2.5200 5.000 0.0000 0.0000 R17
21.2000 2.1200 3.800 0.0000 0.0000 R21
Help
Cancel
Ok
Knowledge Centre WMC
Wind turbine Materials and Constructions


ECN
Define material properties
Blade modelling
1. Define the profiles of the blade
2. Define position of profiles
3. Define lines through the profiles
4. Define materials
5. Define sections
•Define materials by:
•Type
•Isotropic
•Orthotropic
•Core
•Partial material factors according to GL
•Additional material properties can be set for export to FEM
•Material dependent S-N line data (like slope)
•For fatigue analysis
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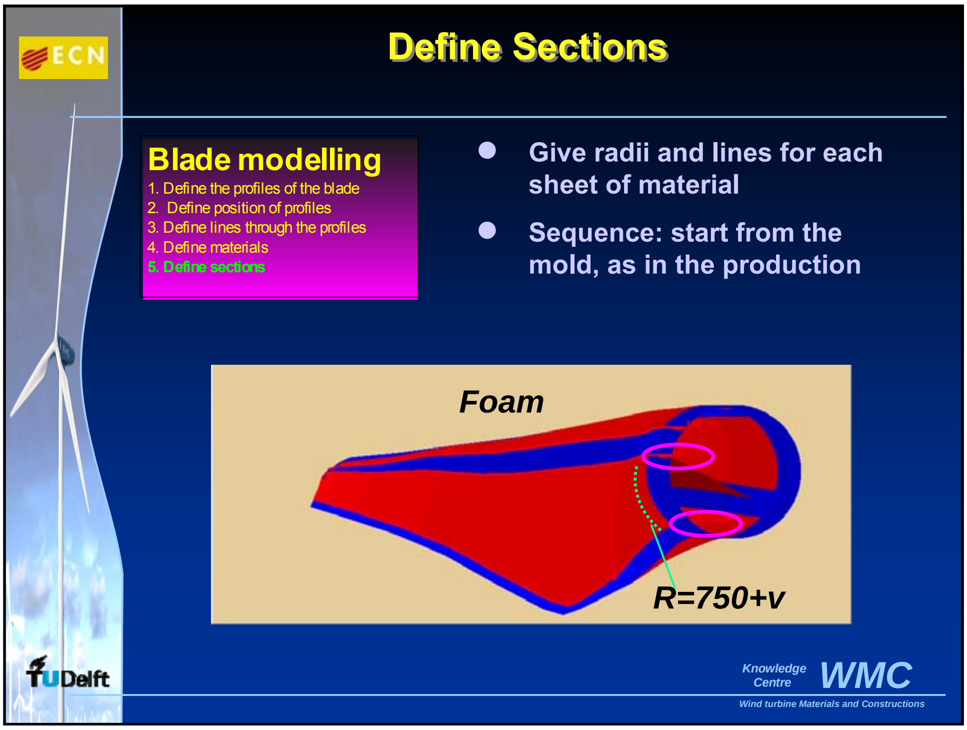
ECN
Define Sections
Blade modelling
1. Define the profiles of the blade
2. Define position of profiles
3. Define lines through the profiles
4. Define materials
5. Define sections
Give radii and lines for each sheet of material
Sequence: start from the mold, as in the production
Foam
R=750+v
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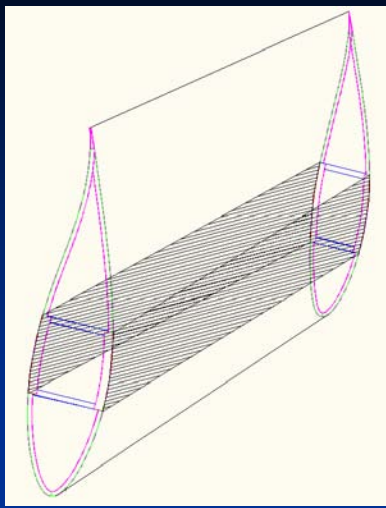
Define Sections (cont'd)

Define layers with ply-angles to introduce bending-torsion or tension-torsion coupling in the blade model



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For analyses we need the bending-twist coupling coefficients

- Estimate of Coupling Coefficients
  - Beam elements that make up the blade model in simulation codes generally have no coupling between the bending and twisting, *g* = 0.

$$\begin{Bmatrix} M_y \\ M_z \end{Bmatrix} = \begin{bmatrix} EI_x & -g \\ -g & GJ \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \phi_x \end{Bmatrix}$$

  - Using anistropic layup, the *g* value represents the coupling stiffness between bending and twisting. The *g* value is limited by the condition that the matrix remains positive definite.

$$g = \alpha\sqrt{EI \cdot GJ}$$

  - For the matrix to be positive definite, the **α** is limited.

$$-1 \le \alpha \le 1$$

  - A non-positive definite matrix has a negative determinant, in this case caused by unrealistic coupling values in the non-diagonal positions.

(sheet: courtesy Mark Capellaro)

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How to determine the coupling coefficients?

- Export blade cross sections from FOCUS
- Use ECN tool CROSTAB to determine the Karaolis/Kooijman coupling coefficients
- Import coupling coefficients in FOCUS

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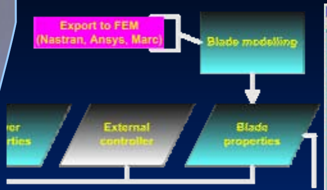
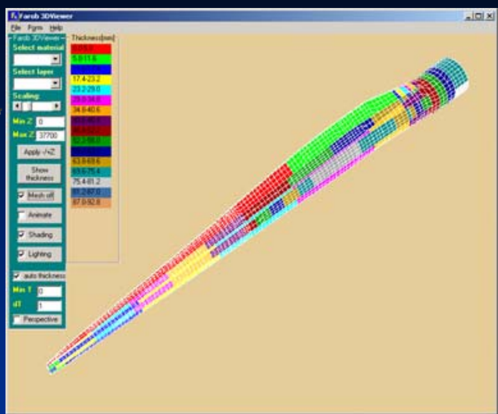
Alternative method





- **MSC.MARC, MSC.Nastran and ANSYS**
- **Thick shell elements**
  - Geometry
  - Materials
  - Full ply lay-up

Export the Focus blade model to your favourite FEM package and use the FEM package to determine coupling coefficients

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FOCUS5 Aerodynamic analyses

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Pre-design rotor blades

Tool: BLADMODE (ECN)

- pre-design of blades
  - Span-wise variation of structural dynamic properties
    - Sweep
    - Pre-bending
- Full aero-elastic analysis
  - or decoupled
  - Torsional deformation
    - Bending-torsion coupling
    - Tension-torsion coupling
- Calculation of power curve without controller.
  - Design of peak-shaving strategy

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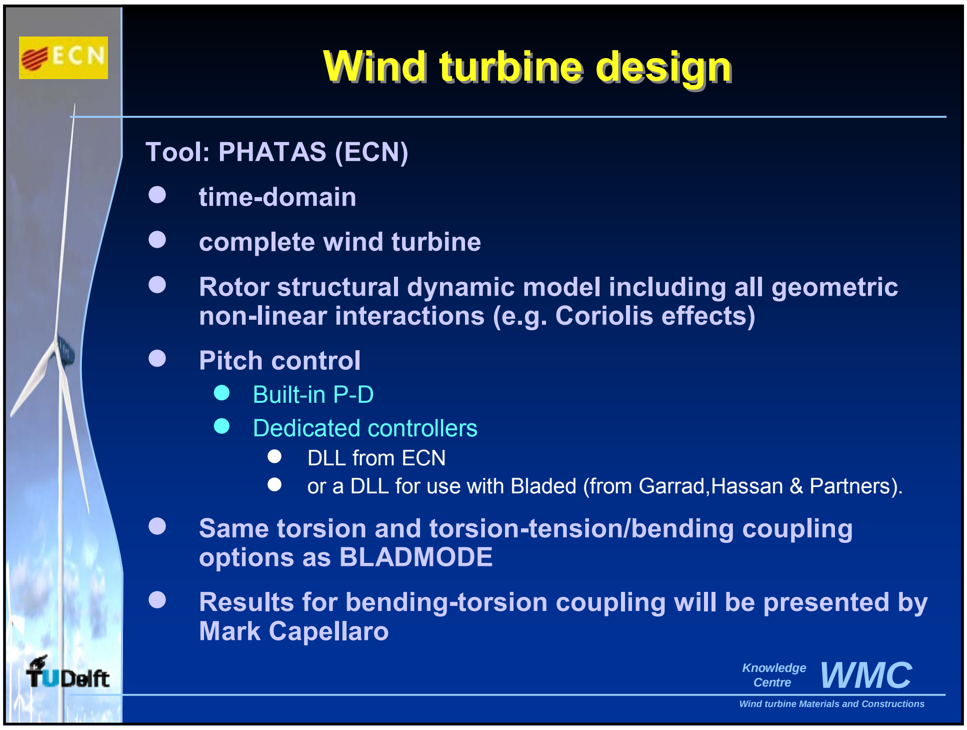
ECN
Wind turbine design
Tool: PHATAS (ECN)
time-domain
complete wind turbine
Rotor structural dynamic model including all geometric non-linear interactions (e.g. Coriolis effects)
Pitch control
Built-in P-D
Dedicated controllers
DLL from ECN
or a DLL for use with Bladed (from Garrad,Hassan & Partners).
Same torsion and torsion-tension/bending coupling options as BLADMODE
Results for bending-torsion coupling will be presented by Mark Capellaro
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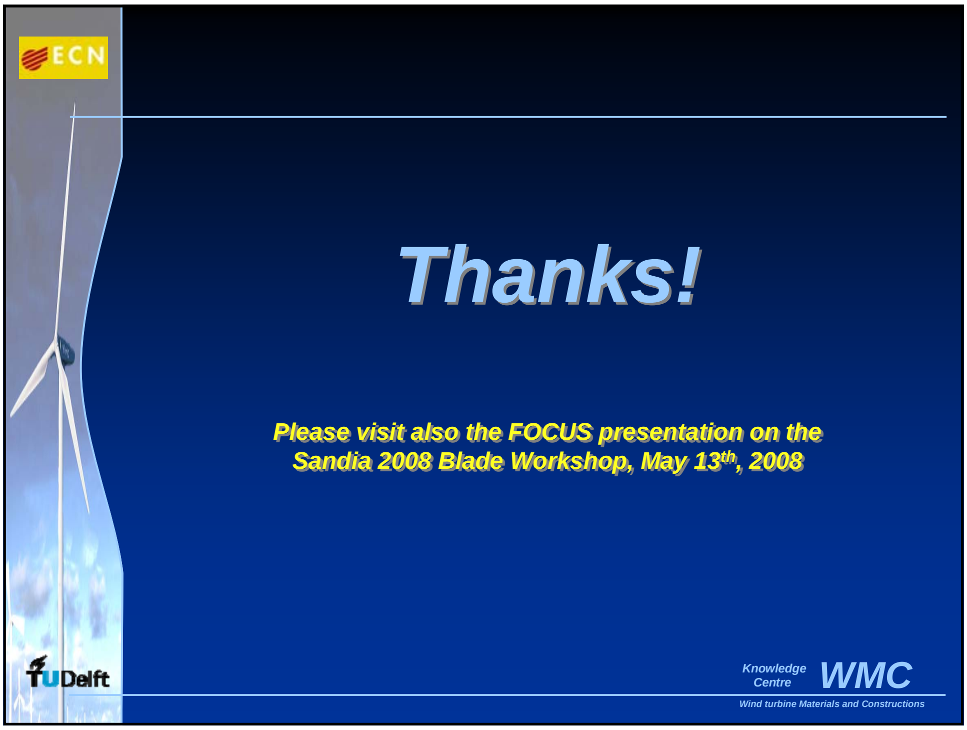

ECN
Thanks!
Please visit also the FOCUS presentation on the Sandia 2008 Blade Workshop, May 13th, 2008
TUDelft
Knowledge Centre WMC
Wind turbine Materials and Constructions

Bend Twist Coupled Blades - Redux

Mark Capellaro
Endowed Chair of Wind Energy at the Institute for Aircraft Design - University Stuttgart
Prof. Martin Kühn

SWE (First German university research chair dedicated to Wind Energy) in Stuttgart

Partial list of topics: (currently 12 researchers)

- **LIDAR**
- **Mitigation of Aerodynamically and Hydrodynamically induced Loads of Offshore Wind Turbines**
- **Load Monitoring and Multivariable Control of Wind Turbines**
- **Dynamic Loading of Wind Turbines in Wake Operation**
- **Load measurement and power curve determination of the Multibrid M5000 prototype**
- **On-line Load Monitoring and Performance Evaluation using Standard Wind Turbine Signals**
- **Multibody Wind Turbine Simulation (SimPack)**
- **Design Wind Turbine Dynamic Modeling Code Comparison**

Stuttgart, Baden Wurtenburg:

Stuttgart, southern Germany, is not known for it's wind power.

However the university has a long history of working with wind energy (Hütter) and composite materials. First large scale fiberglass wind turbine blade was created in Stuttgart.

Institute for Aircraft Design works closely with Airbus and Eurocopter.

Germany's manufacturing center is in the south (Porsche, Mercedes Benz (nee Chrysler), Smart...)

That said, the locals do not like wind turbines.

Bend Twist Coupling – Brief History

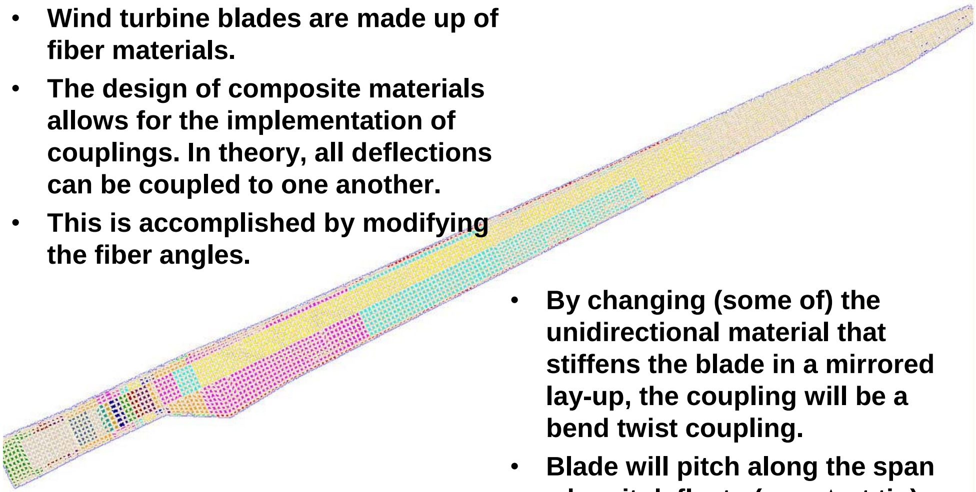
Research about Bend Twist Coupled blades has been performed mostly here in the US (Sandia) or at the ECN (Renewable Energy Center Netherlands)

- The ECN research started in the 90's with an attempt to preclude the use of a pitch mechanism and a twisting direction towards stall.
  - Since then, pitching has become the accepted control mechanism, and usually to feather.
  - Research was promising, with the conclusions reccommending twisting to feather.
- The Sandia research looked at possible ranges of coupling ($-1 > \alpha > 1$) and demonstrated the benefits with turbine simulations.
  - Blades were modeled with simplified coupling coefficients.
- Later FE models (GEC in Seattle) used the ANSYS code to model the blades.

Others: Josh Pacquette (Sandia – design and testing(?)), Alireza Maheri (Bristol – FE modeling and optimization)...

Bend Twist Coupling – How it works*

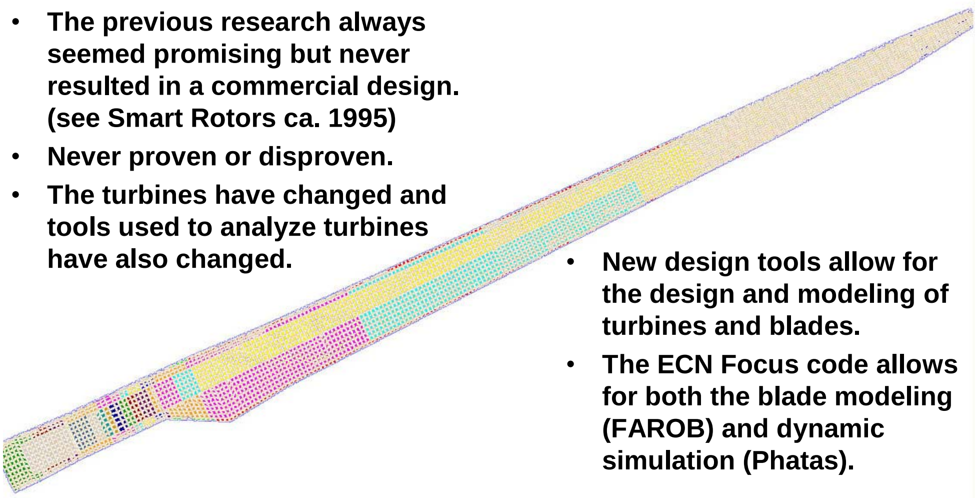
- Wind turbine blades are made up of fiber materials.
- The design of composite materials allows for the implementation of couplings. In theory, all deflections can be coupled to one another.
- This is accomplished by modifying the fiber angles.



- By changing (some of) the unidirectional material that stiffens the blade in a mirrored lay-up, the coupling will be a bend twist coupling.
- Blade will pitch along the span when it deflects (max Δ at tip).

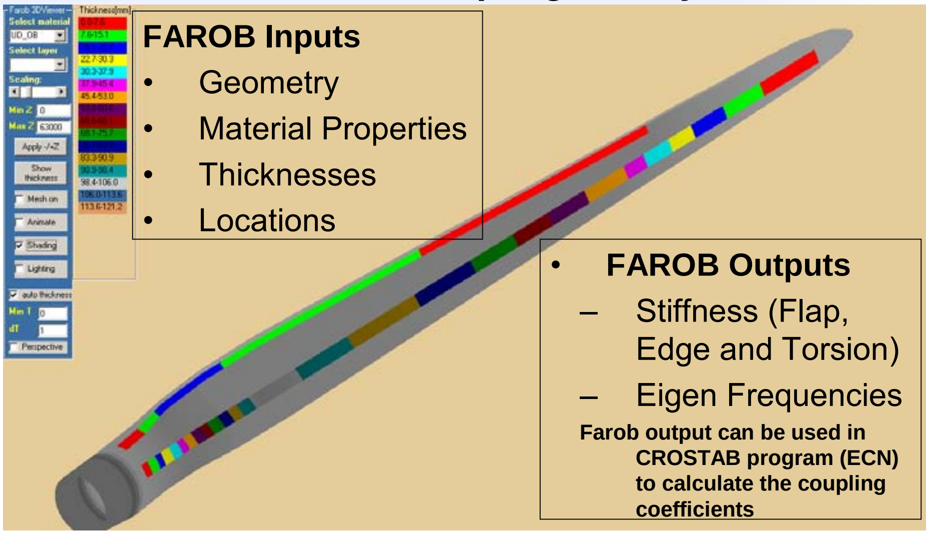
Bend Twist Coupling –

- The previous research always seemed promising but never resulted in a commercial design. (see Smart Rotors ca. 1995)
- Never proven or disproven.
- The turbines have changed and tools used to analyze turbines have also changed.



- New design tools allow for the design and modeling of turbines and blades.
- The ECN Focus code allows for both the blade modeling (FAROB) and dynamic simulation (Phatas).

Bend Twist Coupling - Analysis



FAROB Inputs

- Geometry
- Material Properties
- Thicknesses
- Locations

- **FAROB Outputs**
  – Stiffness (Flap, Edge and Torsion)
  – Eigen Frequencies

Farob output can be used in CROSTAB program (ECN) to calculate the coupling coefficients

Bend Twist Coupling – Preliminary Analysis

Used same method as previous studies

- **Estimate of Coupling Coefficients**
  – **Beam elements that make up the blade model in simulation codes generally have no coupling between the bending and twisting, *g* = 0.**

$$\begin{Bmatrix} M_y \\ M_z \end{Bmatrix} = \begin{bmatrix} EI_x & -g \\ -g & GJ \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \phi_x \end{Bmatrix}$$

  – **Using anistropic layup, the *g* value represents the coupling stiffness between bending and twisting. The *g* values is limited by the condition the matrix remain positive definite.**

$$g = \alpha\sqrt{EI \cdot GJ}$$

  – **For the matrix to be positive definite, the α is limited.**

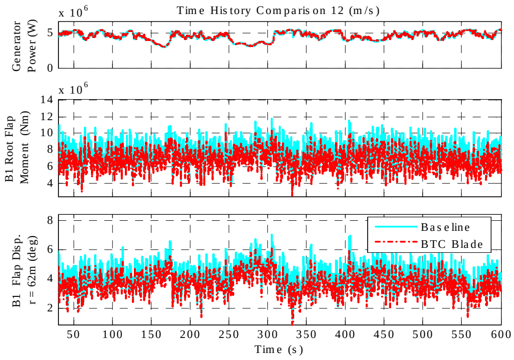
$$-1 \le \alpha \le 1$$

From P. Veers and K. Wetzel.

Bend Twist Coupling – Preliminary Results

α = -0.2 (twist to feather) for BTC blade

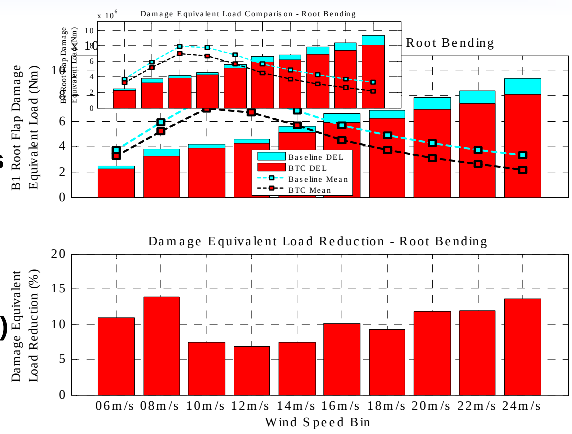
- The results demonstrate that the BTC blade can maintain the same power output and reduce loads.
- Time history comparison shows a decreased load (root flap bending) and decrease in tip deflection.
- Blade twist angle was modified to create an equivalent power turbine.



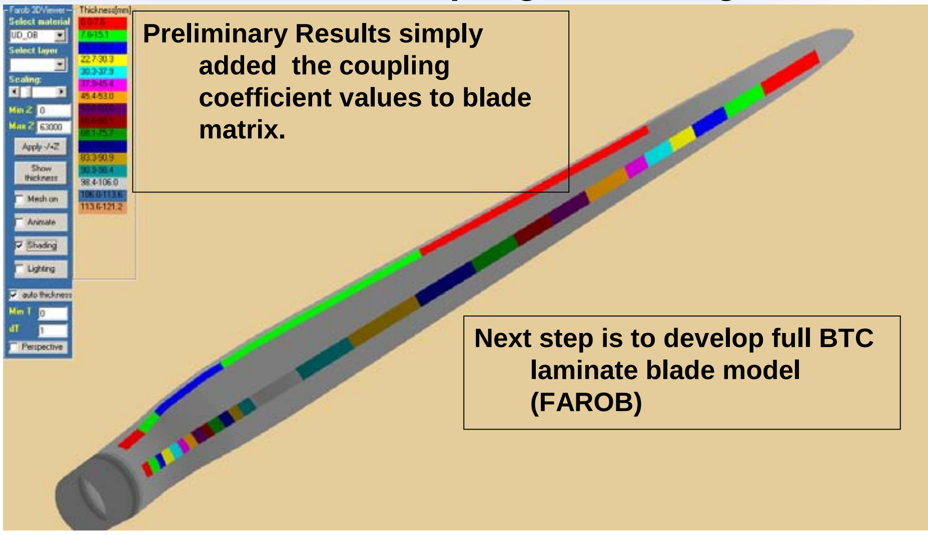
Bend Twist Coupling – Preliminary Results

Load Reduction

- Root Flap Bending load is reduced across all wind speeds.
- Damage Equivalent loads reduced by (average) 10% (Flatwise root bending)



Bend Twist Coupling – Challenges



Preliminary Results simply added the coupling coefficient values to blade matrix.

Next step is to develop full BTC laminate blade model (FAROB)

Bend Twist Coupling – Proposed Methodology

Blade Laminate Design

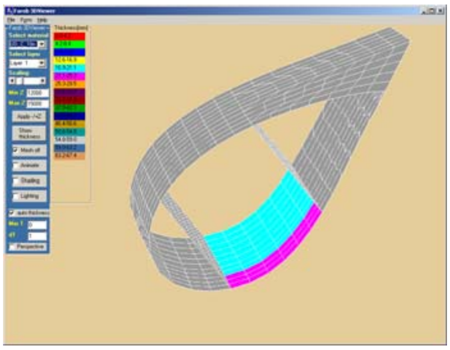
- **<u>Blade Twist Angle</u>: The blade dynamic or coupled twist means that the standard formula to optimize twist below rated (given tip speed ratio) will not work.**
  - **Blade twist angle needs to be developed in a fully dynamic simulation – perhaps at a given wind speed the twist can be optimized.**
- **<u>Bending Stiffness</u>: The off axis fibers would reduce the bending stiffness of the fibers (but the coupled blade may experience lower loads).**
  - **Blade stiffness needs to be designed in a fully dynamic simulation – calculate design load with simulation that includes the twisting.**
- **Other Method: Aero-elastic ‘a priori‘ decision. Determine an optimal bend twist coefficient (α) and develop blade to meet this design criteria.**

Note that changing the angle, amount, material or location of fiber in the blade changes the coupling and the stiffness values. Hence, the model needs to be re-analyzed and re-optimized

Bend Twist Coupling – Next Step

The Upwind Project is an EU project with the goal of developing concepts and methods for tomorrow‘s large turbines (8–10+MW).

- They have a model (originally from NREL) for a 5MW R = 63m bladed turbine
- One Upwind work package is developing Smart Rotors work with active trailing edge control surfaces for the blades.
- The same model is being used in the Bend Twist Coupling modelling.



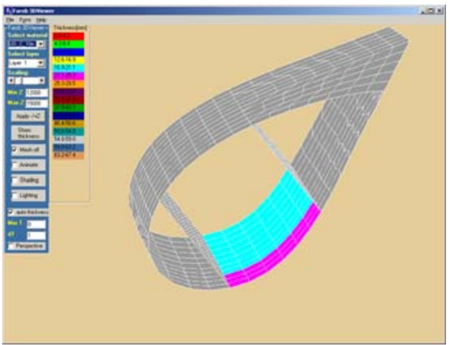
Bend Twist Coupling – Next Step

The WMC has provided a basic composite lay-up schedule for the 63m blade.

Current work involves that model.

The BTC blade will most likely use carbon in the spar caps.

Carbon provides a greater potential for the couplings due to the greater difference between E1 and E2.

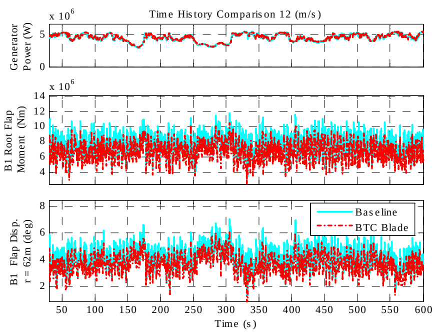


Bend Twist Coupling – Next Step

The IFB has the capability for building composite specimens (two braiding machines, stitching machines, microwave curing, VARI...)

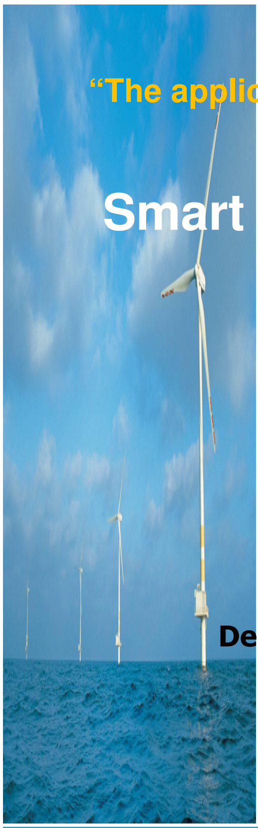
Ongoing student project to build and test an Anisotropic beam in order to demonstrate concept and determine the ability to accurately calculate the coupling coefficients.

Bend Twist Coupling – Conclusion



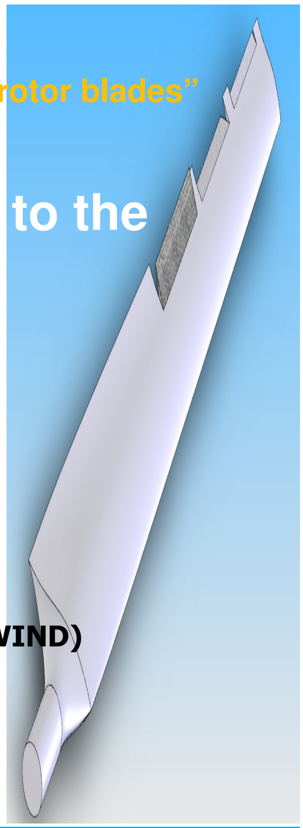
Questions to answer:

- Do the loads go down faster than the blade deflection increases?
- Can an equivalent power criteria be met?
- Can a blade be built?
- How can the decreased fatigue loading be used to optimize the turbine system?



IEA topical expert meeting on
"The application of smart structures for large wind turbine rotor blades"

Smart rotor blade technology applied to the Upwind reference turbine



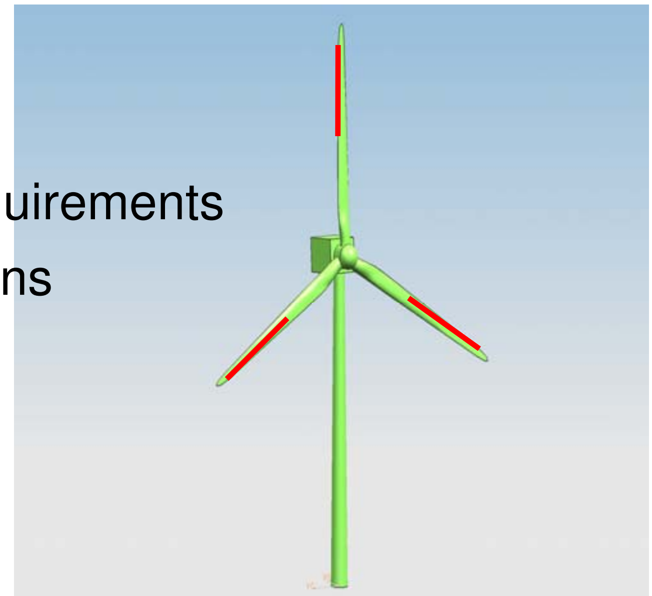
Thanasis Barlas*
and Matthew Lackner

Delft University Wind Energy Research Institute (DUWIND)
Faculty of Aerospace Engineering, Wind energy Section
TUDelft, The Netherlands

*Speaker

Outline

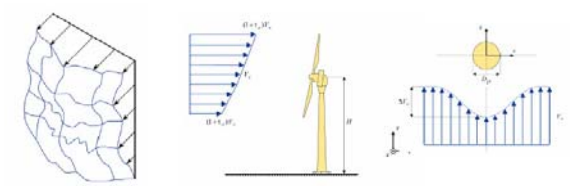
- Introduction
- Analysis of design requirements
- IPC and IFC simulations
- Conclusions

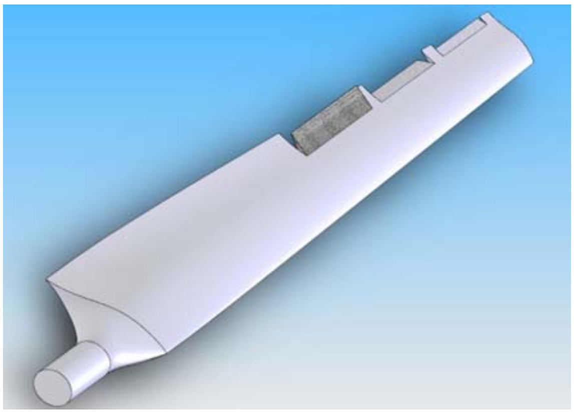


Introduction

Background:

- Actively controlled local aerodynamic surfaces (like flaps) on the blades can efficiently alleviate fatigue loads

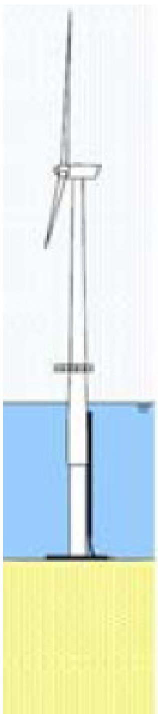




Research questions:

- What are the necessary design requirements for such devices for fatigue and extreme load reduction?
- How important is unsteady aerodynamics?
- What is the load reduction performance compared to IPC?
- What are the issues in combination with existing controls?

Analysis of design requirements



Aeroelastic simulations on the Upwind 5MW RWT:

- Modeled in GH Bladed
- Baseline configuration (i.e. not active load control)
- Representative operating conditions including yaw misalignment and two extreme load cases
- All wind disturbances according to IEC
- Baseline torque and pitch controllers
- Data for tip sections

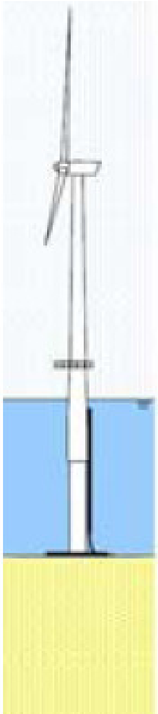
test cases

Av. Wind speed (m/s)	Yaw angle (deg)
8	0
8	15
8	35
11.4	0
11.4	15
11.4	35
18	0
18	15
18	35

radial stations

Station Nr.	r (from blade root) (m)	% r/R
1	47.15	77.20
2	54.66	89.14
3	60.13	97.82

Analysis of design requirements

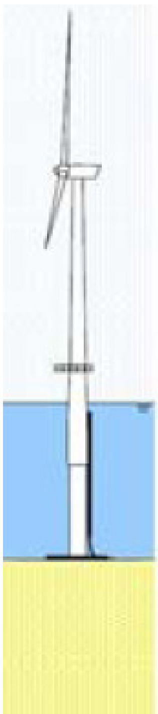


Analysis of aerodynamic changes:

- Statistics for range of amplitudes for aoa and Cl
- Maximum limits around nominal (design) values

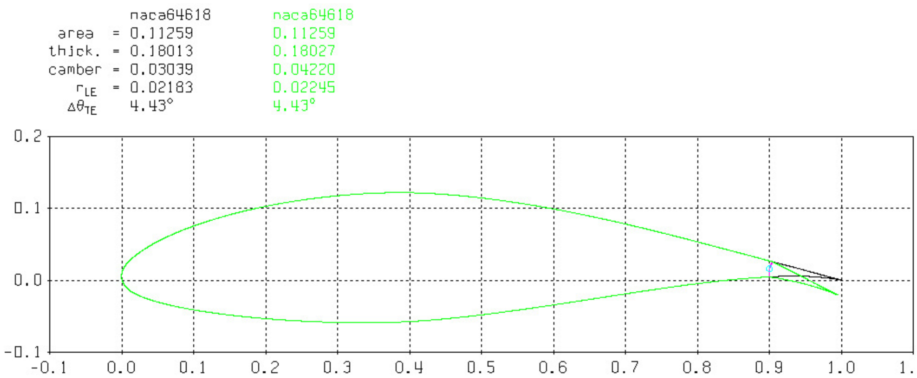
	r=47.15 aoa (deg)	r=47.15 Cl	r=54.66 aoa (deg)	r=54.66 Cl	r=60.13 aoa (deg)	r=60.13 Cl
V∞=8						
Nominal	2.9329	**0.8916**	2.6248	**0.855**	2.2135	**0.8027**
Upper range	6.9627	1.2307	6.2708	1.2175	5.5652	1.1532
Lower range	-0.7528	0.3484	-0.5723	0.4766	-0.5221	0.4781
V∞=11.4						
Nominal	2.7404	**0.8691**	2.0436	**0.7875**	-0.8893	**0.4346**
Upper range	7.9285	1.362	6.7096	1.2568	6.2303	1.2118
Lower range	-0.585	0.4759	-0.4797	0.4887	-1.0219	0.4178
V∞=18						
Nominal	-1.7215	**0.3379**	-2.4585	**0.2478**	-6.4995	**-0.2352**
Upper range	7.2418	1.305	4.7506	1.0746	4.0264	1.012
Lower range	-5.5905	-0.1275	-5.8797	-0.161	-5.1323	-0.754

Analysis of design requirements

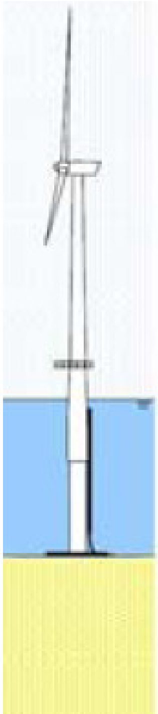


Analysis of control requirements:

- Max/Min Cl at specific aoa
- Analysis for a 5% and 10% rigid TE flap
- Required flap angles to compensate



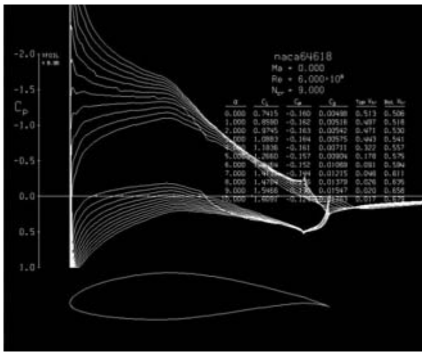
Analysis of design requirements



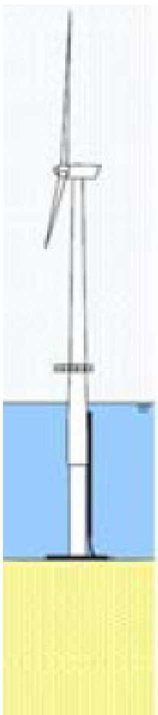
Analysis of control requirements:

- max +-15 deg. deflection of a 5%c flap is not enough
- max +-12 deg. deflection of a 10%c flap can alleviate all disturbances
- control surface design and actuator performance will set the real max limits (saturation)

	aoa (deg)	Cl
max upper range of all cases:	7.9285	1.362
max lower range of all cases:	-5.8797	-0.754
max flap angle for all cases:	>-15 to >+15	with a 5%c flap
max flap angle for all cases:	-12 to 12	with a 10%c flap



Analysis of design requirements

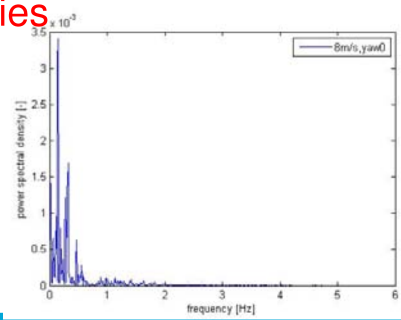


Analysis of aerodynamic unsteadiness:

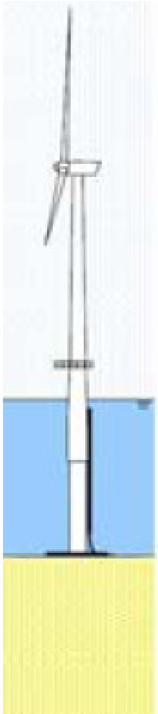
- Unsteady motions: aoa/torsion/pitch, flap/edge bending
- Reduced frequency $\kappa = \frac{\omega \cdot c}{2 \cdot V}$
- Unsteady flow: k>0.05 $\kappa = \frac{\omega \cdot c}{2 \cdot Vres} > 0.05 \Rightarrow \omega > \frac{0.05 \cdot 2 \cdot Vres}{c}$
- Frequency limits for unsteadiness identified
- For all cases: from 0.24Hz to 0.89Hz
- Effect of upscaling: limits slightly drop
- Quantification of importance: PSD areas
- 5% - 65% of PSD in unsteady frequencies

r=54.66

V (m/s)	Ψ (deg)	Integ. steady	Integ. unsteady	ratio of unsteady/total (%)
8	0	0.000134	0.000235	63.56
8	15	0.000235	0.000051	17.99
8	35	0.000353	0.000055	13.44
11.4	0	0.000093	0.000040	30.02
11.4	15	0.000180	0.000037	16.85
11.4	35	0.000418	0.000044	9.49
18	0	0.000348	0.000530	60.38
18	15	0.000530	0.000070	11.73
18	35	0.000981	0.000057	5.53



Analysis of design requirements

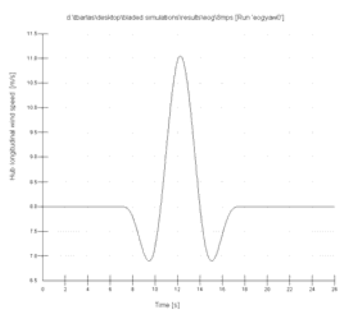


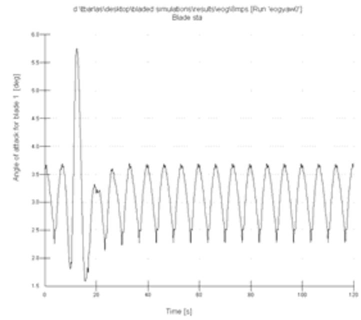
Extreme load cases:

•IEC Extreme Operating Gust and Extreme Direction Change

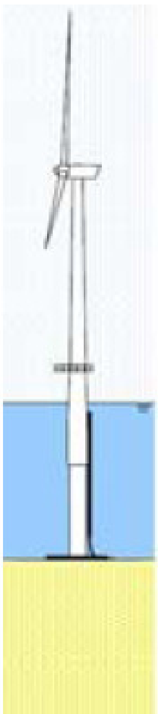
•max +-15 deg. deflection of a 10%c flap can alleviate all disturbances in the EOG

•max +-5 deg. deflection of a 10%c flap can alleviate all disturbances in the EDC





Analysis of design requirements



Fatigue content analysis:

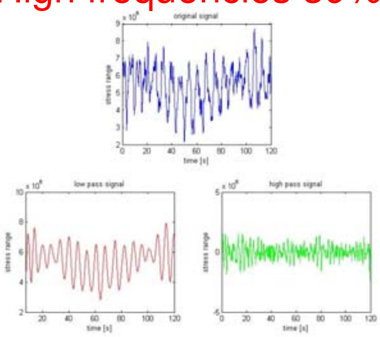
•From PSD identified required max control bandwidth

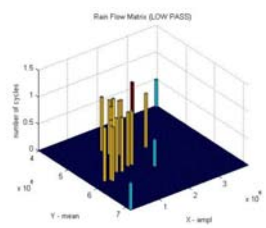
•~0 to 6Hz bandwidth required to cover all disturbances

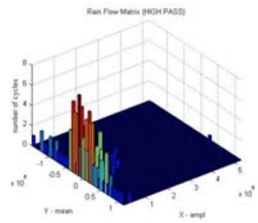
•Contribution of freq. regions to fatigue:

- •Convert blade root flap moment to stress $\sigma_{root} = \frac{M_{root} \cdot c}{I_{root}}$ $I_{root} = \frac{\pi}{64}(D_{outer}^4 - D_{inner}^4)$
- •Filter stress signal to low (<1p) and high (>1p) frequencies
- •Apply Rainflow Counting
- •Calculate equivalent loads $Deq = \left(\frac{\sum_i ni \cdot Di^m}{f \cdot T} \right)^{1/m}$

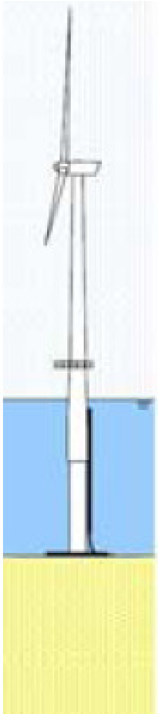
•High frequencies 39% to 61% of total fatigue loads!





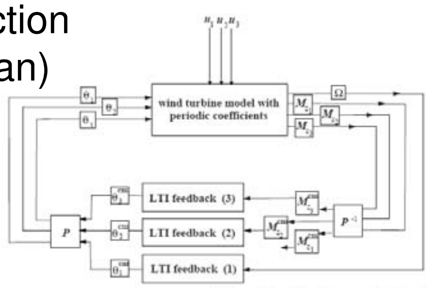


IPC and IFC simulations



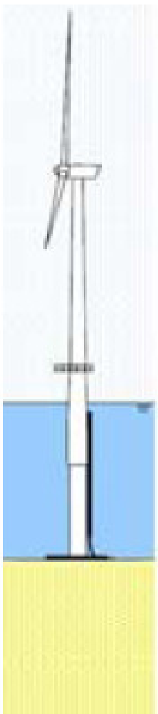
Active load control simulations:

- "tweaked" Bladed
- 20%R span large flap
- 10%c chord-wise flap length
- Max flap deflections +-10 deg
- Max flap rates +-40 deg/s
- Tabulated flap effect (quasi-steady)
- Same baseline torque and collective pitch controllers
- Either IPC or IFC added for load reduction
- Multi-rotational transformation (Coleman)
- Collective flap angle optionally used for power regulation (region 3)



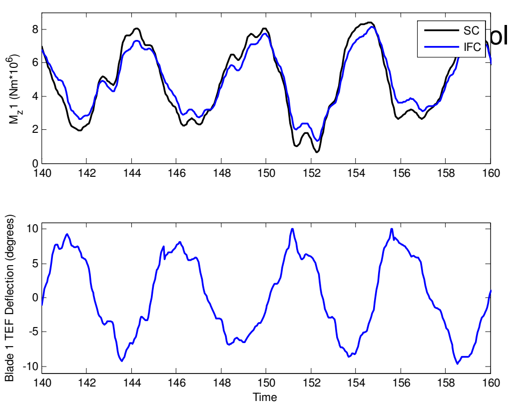
T.G. van Engelen, E.L. van der Hooft

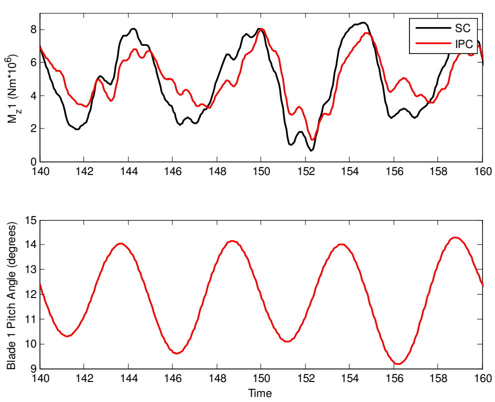
IPC and IFC simulations



Time domain visualization:

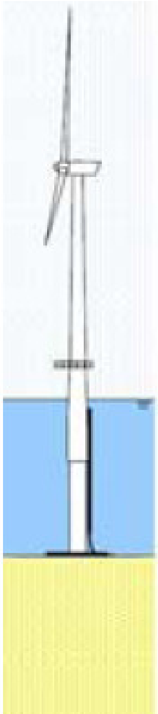
- Segment of the results of the 16 m/s simulation:





IPC and IFC simulations

Load reduction results:



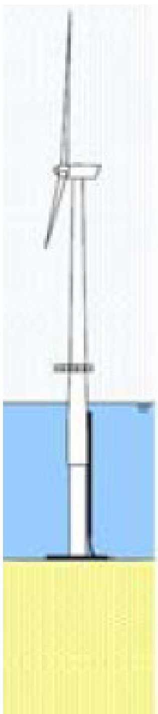
- Quantify using standard deviation of the root flapwise bending moment.
- Normal turbulence levels:

	SC	IFC		IPC	
Mean Wind Speed $[m/s]$	$\sigma(M_z)$ $[Nm * 10^6]$	$\sigma(M_z)$ $[Nm * 10^6]$	Reduction [%]	$\sigma(M_z)$ $[Nm * 10^6]$	Reduction [%]
8	1.45	1.31	-9.7%	1.45	0%
12	1.66	1.37	-17.6%	1.66	0%
16	2.04	1.74	-14.7%	1.70	-16.5%
20	2.16	1.86	-13.9%	1.70	-21.1%

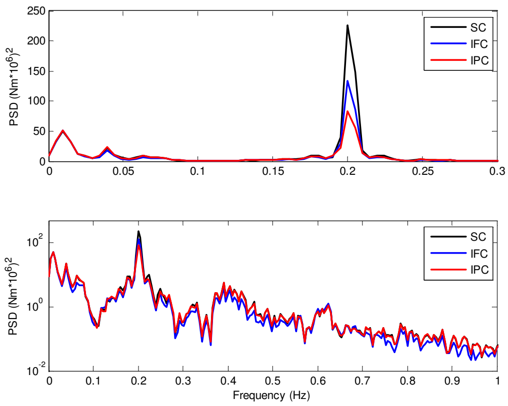
UpWind DUWIND DELFT UNIVERSITY WIND ENERGY RESEARCH INSTITUTE TU Delft

IPC and IFC simulations

Load reductions in the frequency domain:



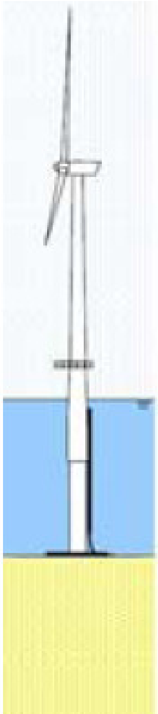
- Large 1P peak.
- Effectiveness depends on frequency of the loads.
- Most energy in the low frequency range
- Flaps have much higher bandwidth.



Frequency Region	% of Total Energy	Reduction: IFC [%]	Reduction: IPC [%]
Low	88%	-27.6%	-34.2%
High	12%	-37.3%	-1.2%

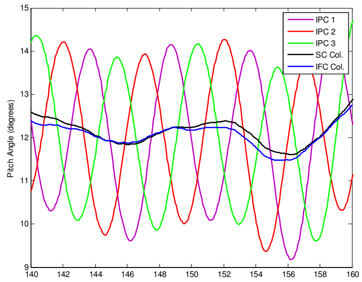
UpWind DUWIND DELFT UNIVERSITY WIND ENERGY RESEARCH INSTITUTE TU Delft

IPC and IFC simulations



Effects on pitch system:

- Different approaches affect the pitch system differently.
- Use 16 m/s simulation to investigate.



- Pitch Angle:

	SC	IFC		IPC	
Mean Wind Speed $[m/s]$	$\sigma(\theta)$ $[deg]$	$\sigma(\theta)$ $[deg]$	Change [%]	$\sigma(\theta)$ $[deg]$	Change [%]
12	3.04	2.96	-2.7%	3.33	9.6%
16	3.39	3.30	-2.8%	3.58	5.5%
20	3.22	3.10	-3.5%	3.49	8.5%

- Pitch Rate:

	SC	IFC		IPC	
Mean Wind Speed $[m/s]$	$\sigma(\dot{\theta})$ $[deg/s]$	$\sigma(\dot{\theta})$ $[deg/s]$	Change [%]	$\sigma(\dot{\theta})$ $[deg/s]$	Change [%]
12	0.28	0.26	-7.6%	2.25	701%
16	0.35	0.32	-10.0%	1.21	242%
20	0.27	0.24	-10.5%	1.21	354%

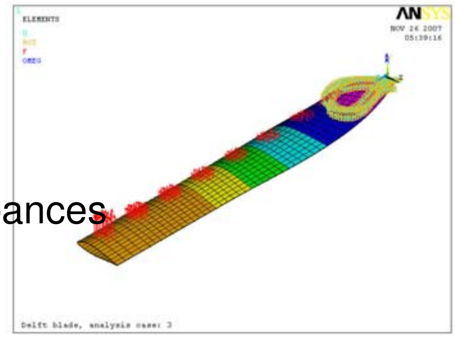
Conclusions

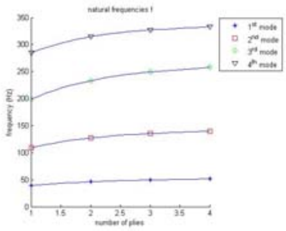
- Main design requirements, in terms of load reduction performance, are analyzed and limits are set. Key issues identified.
- Aerodynamic unsteadiness should be taken into account.
- Reasonable 10%c flap angles required for full control authority.
- Other design limitations will affect the load reduction performance (e.g. actuator capabilities, structural design, sensor s)
- Active flap control can contribute to high frequency load reduction, which is important for fatigue.
- IFC is comparable to IPC and beneficial at high frequencies.
- Distribution of control surfaces should be optimized
- Smart control generally beneficial when incorporated in existing control schemes.

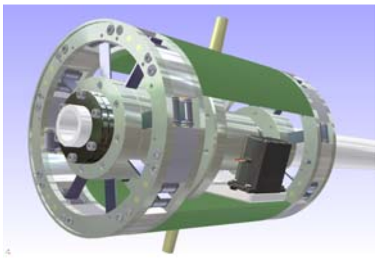
Upcoming Experiments

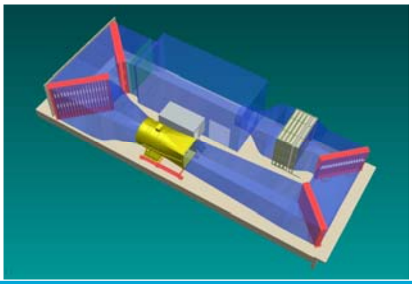
Rotating wind tunnel experiments:

- 2-bladed 1.8m diameter rotor in OJF tunnel
- Scaled blade dynamics
- Active piezoelectric flaps
- Scaled periodic and stochastic wind disturbances
- Real-time controller
- Beginning late 2008









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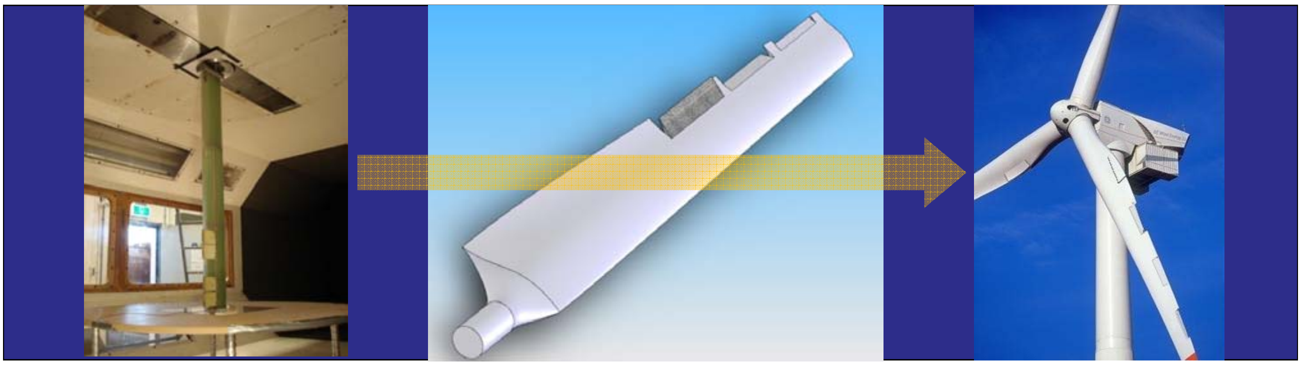

Questions?

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Variable Geometry Airfoils and Active Flow Control

Sridhar Kota
FlexSys Inc., Ann Arbor, MI
http://www.flxsys.com

Professor, Mechanical Engineering
University of Michigan, Ann Arbor

FlexSys Inc.

IEA Blade Workshop, Sandia National Labs
May 8-9, 2008

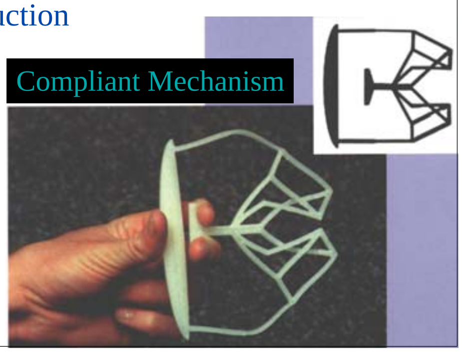
Flex to Function

Elastic deformation as a preferred effect in mechanical design to achieve controlled motion and force transmission.

•Elimination of Joints
No Assembly, No Friction, No Wear, and No Clearance

•Reliable and High Precision Operation

•Simple and Cost-effective Construction

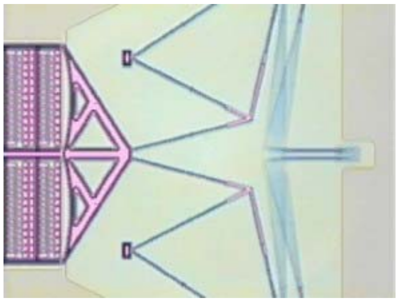


FlexSys Inc.

Micro Scale Amplifiers

Size:

110 microns x
150 microns



Various MEMS actuators (with amplifiers ranging from 12X to 60X) were fabricated using Sandia National Lab's SUMMiT-V advanced 5-level surface micro machining process (1998). The device shown is operating at 27 KHz, tested up to 10 billion cycles without failure.

FlexSys Inc.

Outline

Introduction and Benefits of Compliant Structures

- Fixed Wing
- Mission Adaptive Compliant Wing

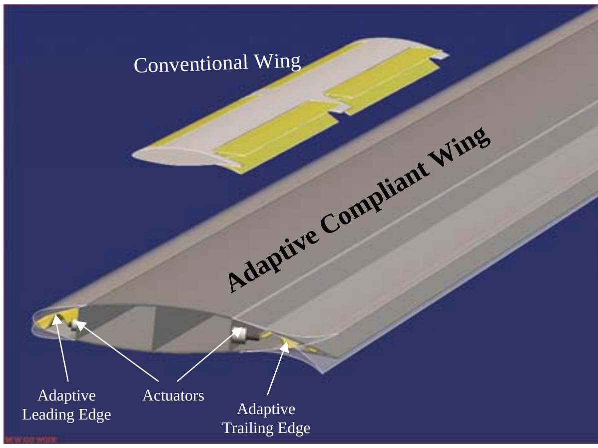
Rotor blade:

- Variable Geometry Leading Edge
- Variable Geometry Trailing Edge

High Frequency Vortex Generators

FlexSys Inc.

Variable Geometry Control Surfaces



FlexSys Inc.

Observations on Morphing

Benefits of seamless control surfaces or shape morphing are well understood by the aerospace community since Wright Brothers

Shape Morphing involves structural *deformation*. Yet, majority of the research in morphing has not exploited elasticity of the underlying structure.

Using plethora of "smart" actuators to morph a rigid structure led to designs that are too heavy, too complex, requiring too much power.

Morphing versus Actuator; Transmissions

Scalability

FlexSys Inc.

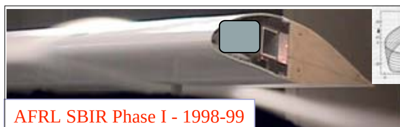
Compliance Enables Morphing

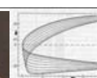
Exploiting elasticity of the underlying structure, or use of compliant structures, led to designs that are

- Seamless
- Strong and compliant
- Scalable
  - -full scale variable geometry surfaces (LE,TE) in fixed wing and rotor blade applications.

- Lightweight
- Less power
- Durable (no moving parts- monolithic mechanism)

FlexSys Inc.

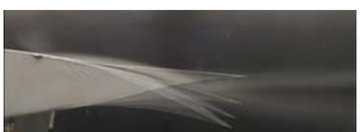




Patents 5971328, 6491262, 1047593, DE 69934210T2, WO 145718 A2, others pending

AFRL SBIR Phase I - 1998-99

SBIR Phase II 2000-02 HiLDA Airfoil
+/-10 deg flap deflection with 3 deg span-wise twist

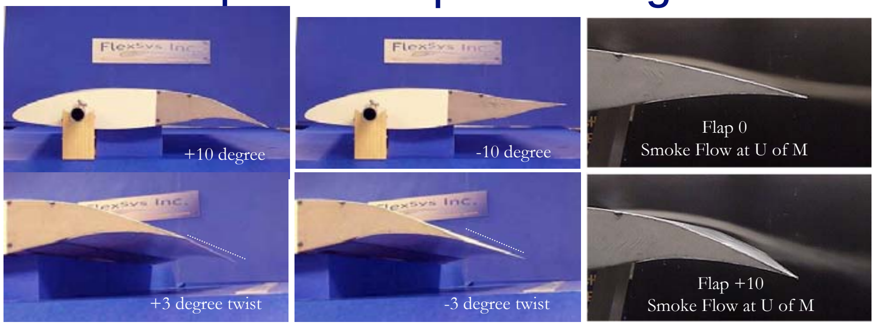


Low-speed wind tunnel test;
Minimum drag penalty as CL changed from 0.1 to 1.1

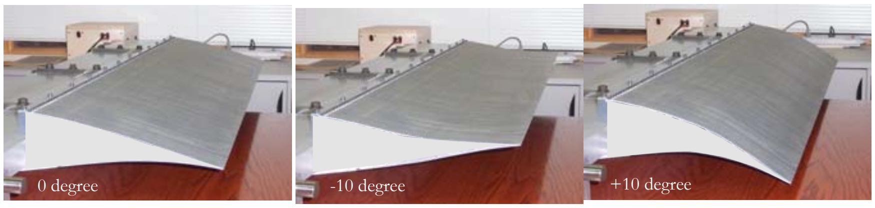
Structural test model – 2003

Flight test model - 2006

Mission Adaptive Compliant Wing



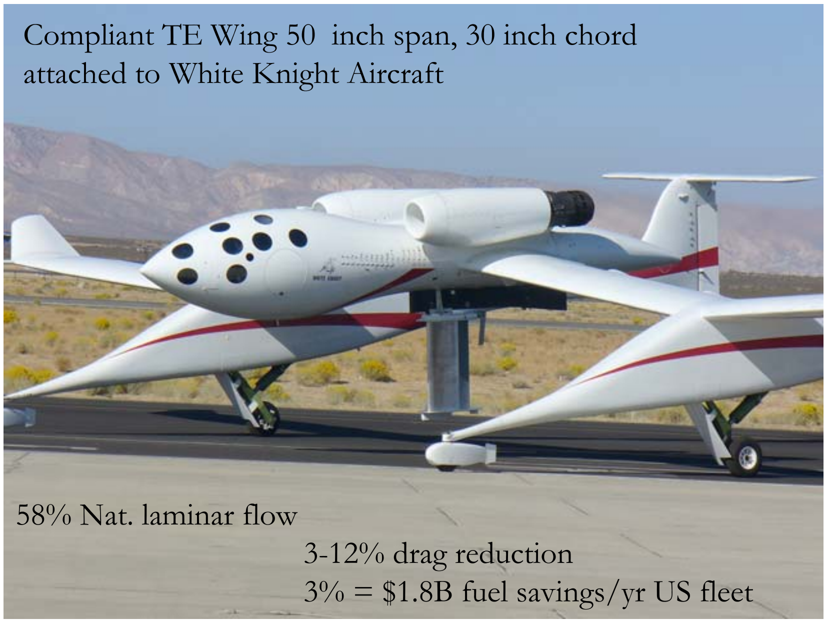
Low Speed Wind Tunnel Model (2003)



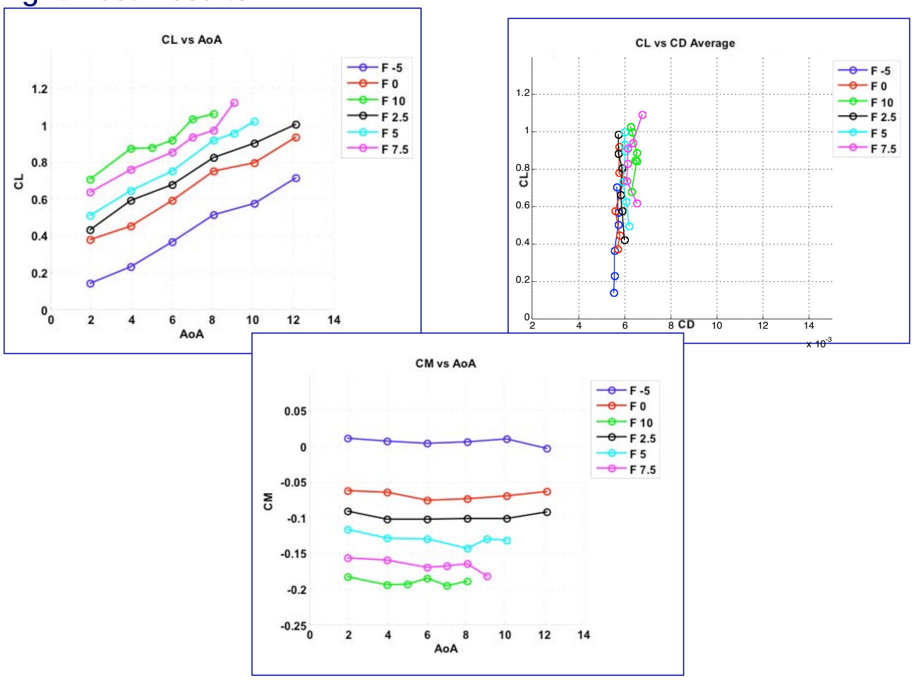
Structural Test Model (2004)

Patents 5971328, 6491262, 1047593, DE 69934210T2, WO 145718 A2, others pending

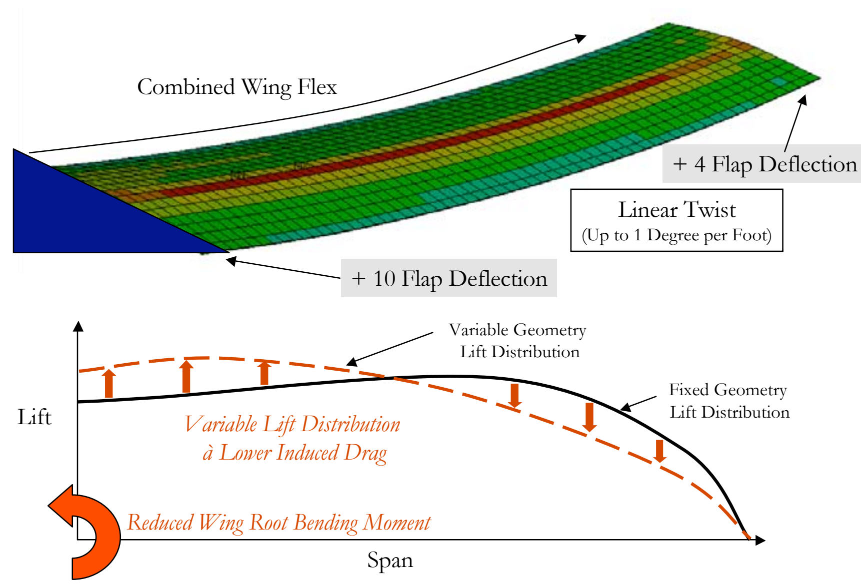
Flight Test



Flight Test Results



Span-wise Load Control



Weight Reduction

Compared to Conventional Flap

- A smaller chord MAC-Wing flap
  - 30% weight reduction since a 25-30% smaller chord flap is needed for equivalent aerodynamic performance
- Variable twist for span-wise load tailoring
  - Decrease wing weight due to a reduction in the wing root bending moment
- For military applications:
  - MACW flaps may not require signature reducing materials – a further saving in weight

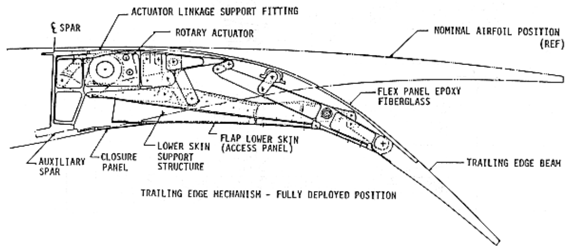
A "ground-up" design exploiting all MAC-Wing benefits can result in an overall aircraft weight savings

Other Key Advantages

- High Rate Capable
  - Limited only by actuation rates
- Materials Friendly
  - Aluminum, Titanium, Composites, etc.
- Monolithic Flap Structure
  - Simplifies mechanical architecture of variable camber device
  - Ample load path redundancy – fault tolerant structure
  - No gaps or hinges
  - Zero backlash
- Possible Size Reduction
  - Equivalent authority flap can be smaller
  - Increases wing box chord

Excellent Aero Performance;

Structurally…. Too Complex and Too Heavy



Mission Adaptive Wing Air Force Research Labs, 1987

Simplicity by Design

Adaptive Compliant Wing

Simply Exploits Material Elasticity

Structurally…Lighter, Less power, No Moving Parts
Significant Improvement in Aero Performance

Design Challenge: Compliant to the actuator to minimize energy needed to morph YET stiff enough to without external loads

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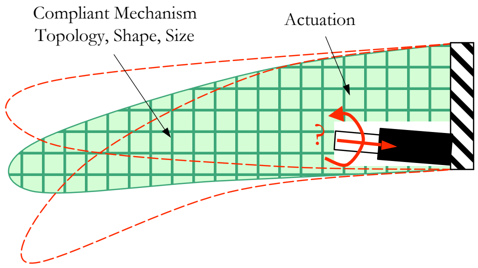
Design Challenge

Compliant to the actuator to minimize energy needed to morph YET strong and stiff enough to without external loads(pressure, inertial)

FlexSys Inc.

Designing with Distributed Compliance



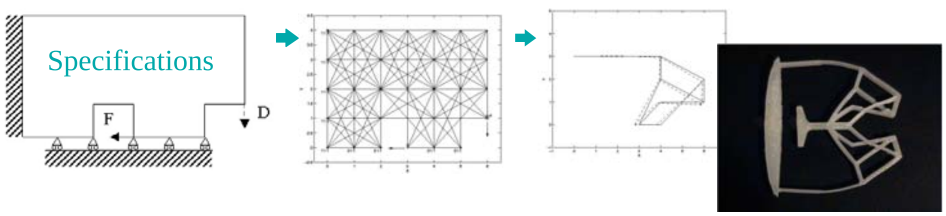
Shape Morphing Task

Design Inputs:
- Shape Morphing Targets
- Matching Tolerance
- Pressure Profiles
- Material Characteristics
- Stress Limits
- Required Stiffness Under Load
- Required Dynamic Behavior
- Actuator characteristics

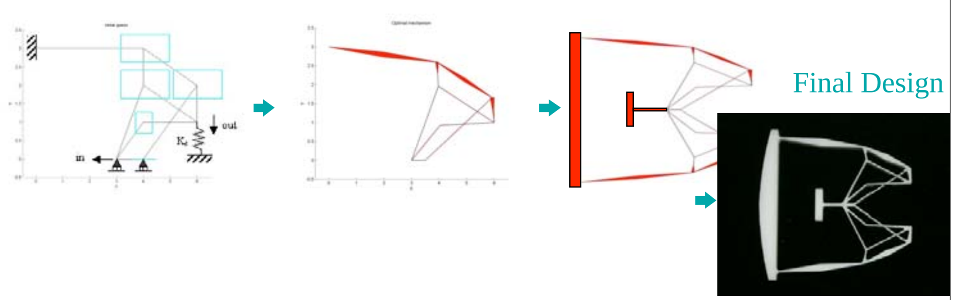
Structure Optimized For:
- Minimum Actuator Force
- Minimum Weight
- Satisfy all Constraints
  - stress
  - buckling
  - fatigue
  - shape matching

Overview of the Design Process

Stage 1: Topology design. – a functional design configuration

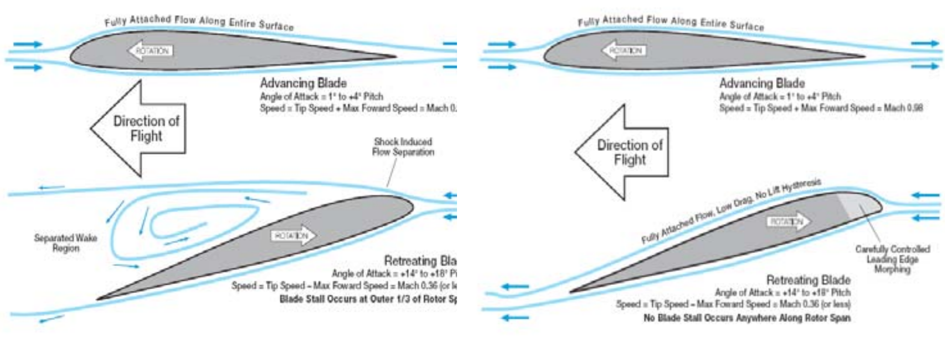


Stage 2: Size/geometry design – meets performance requirements & constraints



Variable Geometry Rotor Blade Complaint Leading Edge

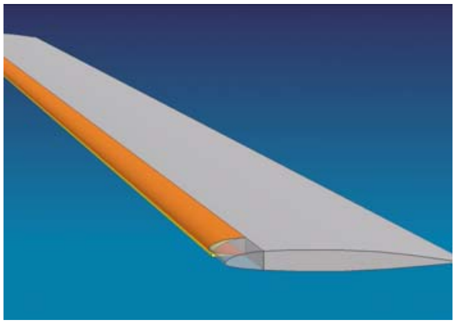
Variable Geometry LE



Sikorsky SSC-A09

Variable Geometry Leading Edge

Army Phase II SBIR Subcontract - 2004



10 degree droop

Once per revolution (6Hz)

Single actuator in the LE

8.5% flap chord

Air loads and inertial loads (1000g centrifugal load)

Designed to last 220 million cycles

126 Watts/ft.

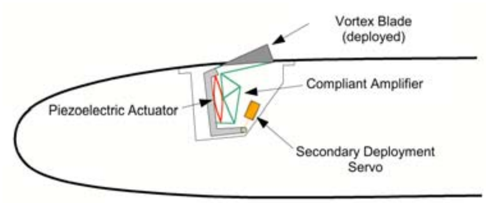
4.3 lbs/ft.

FlexRotor

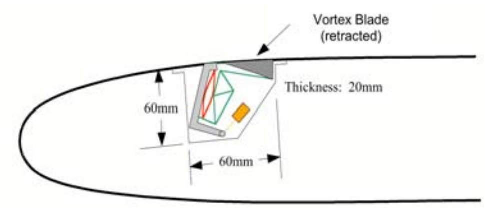
Variable Geometry Trailing Edge Rotor Blade

Active Flow Control using High Frequency Micro Vortex Generators

Vortex Generator - Deployed



Vortex Generator - Retracted

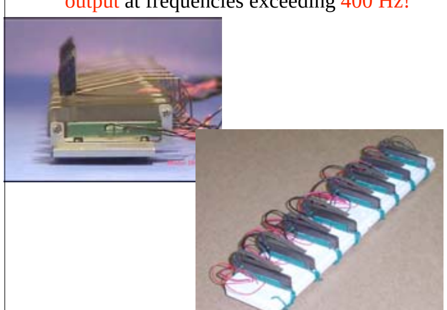


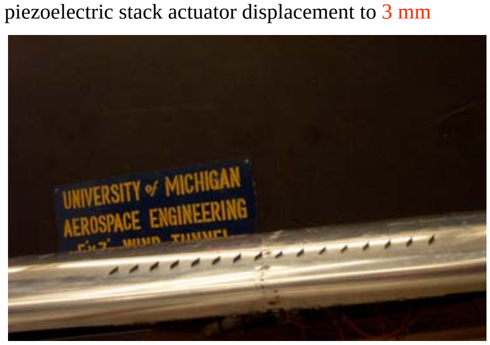
High-Frequency Micro Vortex Generator (0-800 Hz)

Patents 6175170,6557436

Other U.S. & Foreign Patents Pending

Compliant displacement amplifiers (65X) amplify piezoelectric stack actuator displacement to 3 mm output at frequencies exceeding 400 Hz!





Adaptive Blades for Wind Turbines

Increase L/D

Reduce structural loads

Composite trailing edge flaps

Up to +/-40 deg of deflection at 100 deg/sec

Span-wise twist +/- 20 deg

No moving parts in the mechanism

Can be integrated with a different types of actuators

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A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Sandia National Laboratories

U.S. Department of Energy
Energy Efficiency and Renewable Energy

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Objectives

- Create design methodology for advanced controls:
- Develop control design and modeling tools for industry.
- Apply controls to commercial machines.

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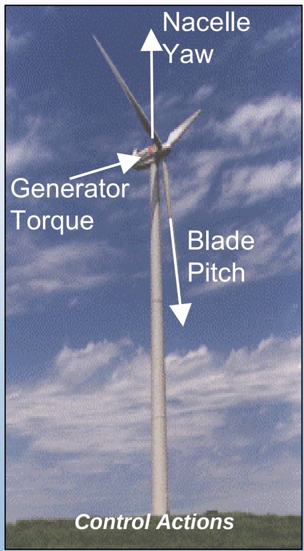
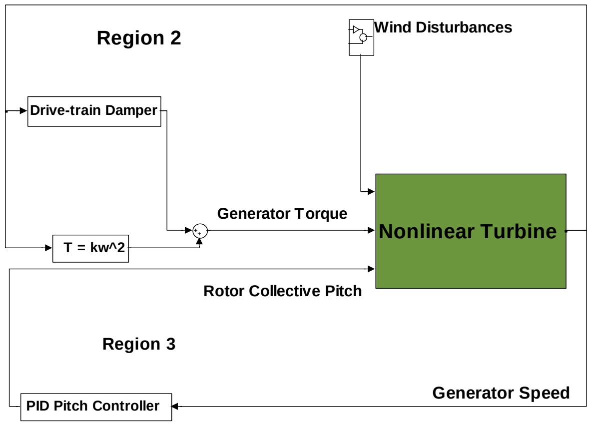
Commercial Turbine Control



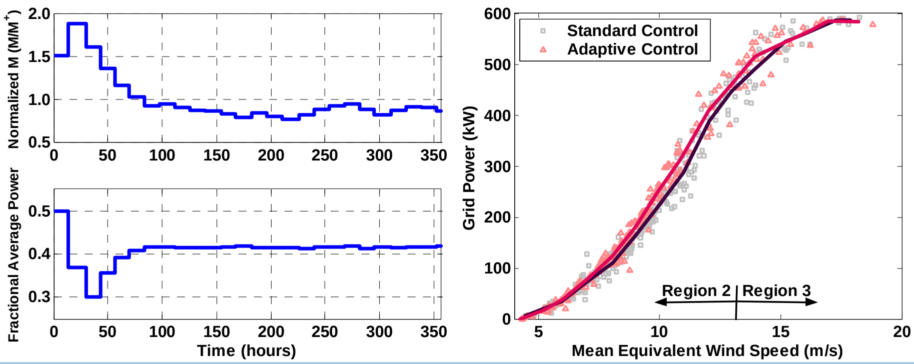


What else can we do?

- **Improve energy capture**
  - Active rather than passive rotor control
    - Negative inertia - Use of shaft torque to cancel rotor inertia
  - Adaptive control
  - Optimal torque control

- **Reduce loads**
  - Load feedback
  - Independent pitch control
  - Active tower / blade / drive-train damping
  - Advanced sensors
  - Look-ahead controls

Adaptive control
0.3% - 5% energy capture increase



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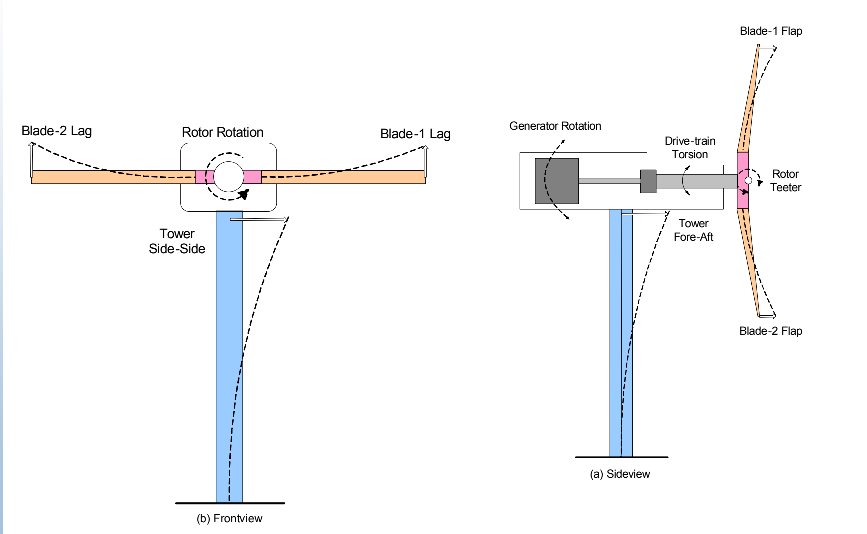
Control of Flexible Modes



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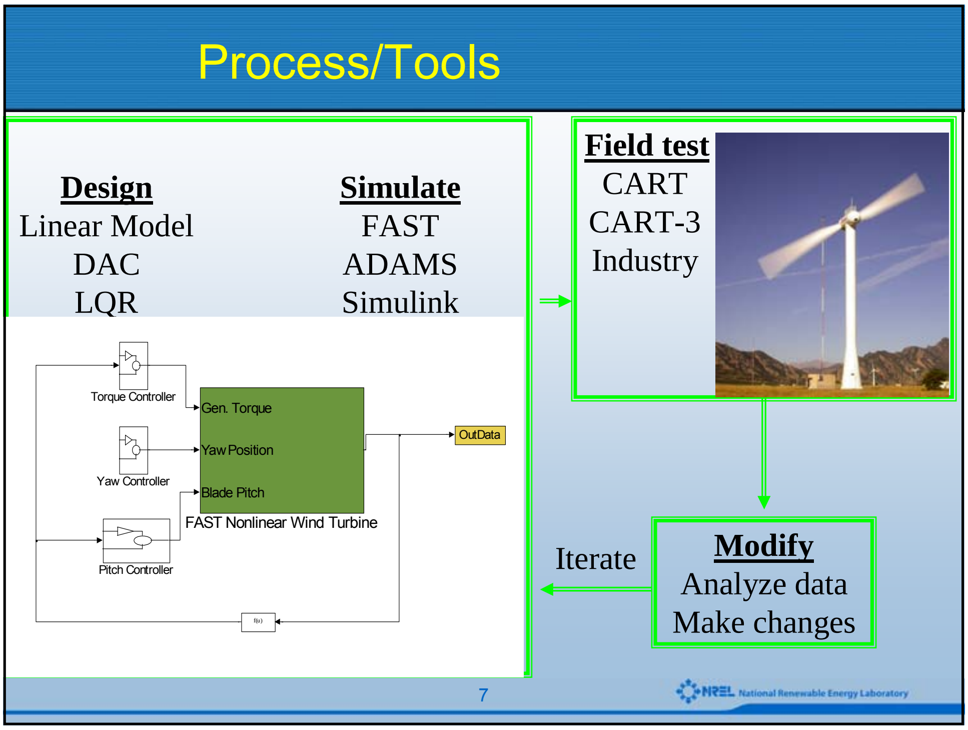
Process/Tools
Design
Linear Model
DAC
LQR
Simulate
FAST
ADAMS
Simulink
Torque Controller
Yaw Controller
Pitch Controller
Gen. Torque
Yaw Position
Blade Pitch
FAST Nonlinear Wind Turbine
OutData
Field test
CART
CART-3
Industry
Iterate
Modify
Analyze data
Make changes
7
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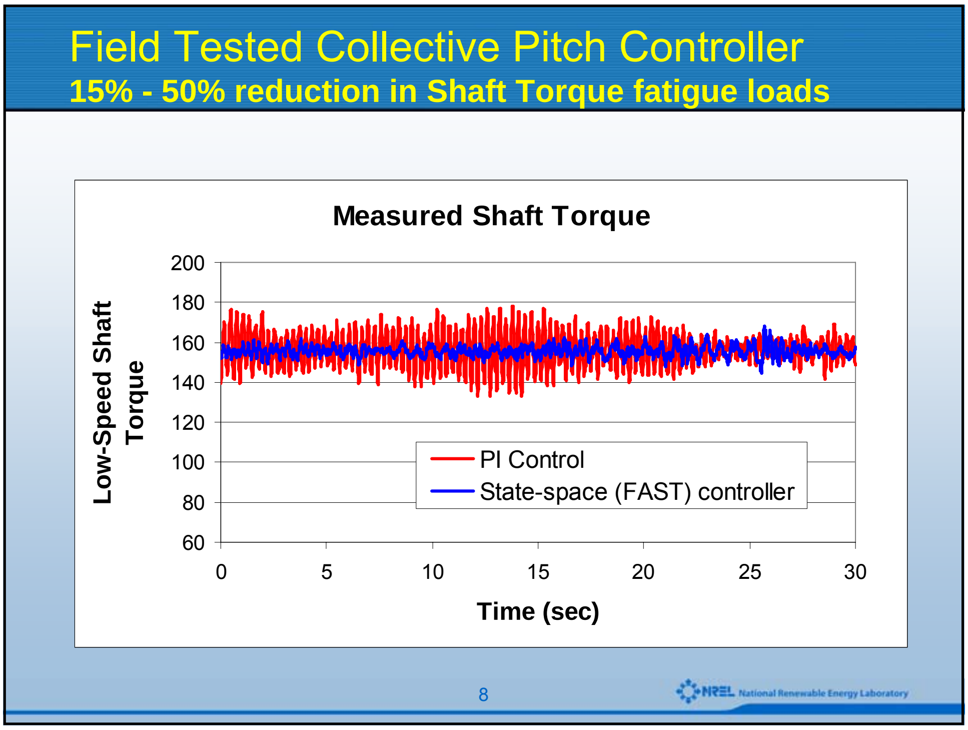
Field Tested Collective Pitch Controller
15% - 50% reduction in Shaft Torque fatigue loads
Measured Shaft Torque
Low-Speed Shaft Torque
200
180
160
140
120
100
80
60
0
5
10
15
20
25
30
Time (sec)
PI Control
State-space (FAST) controller
8
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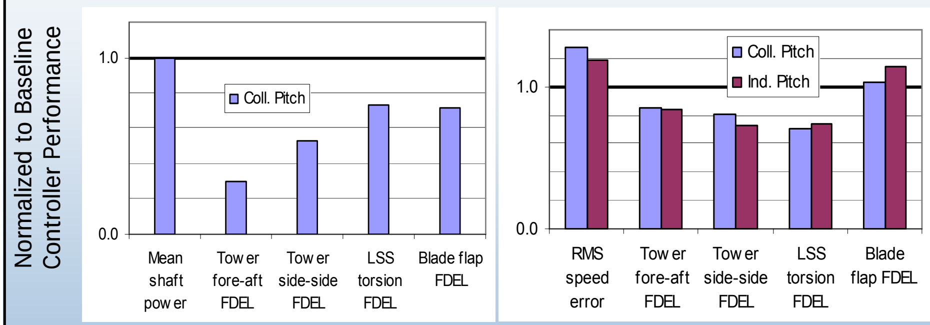
CART Test Results – Pitch Control

Region 2 | Region 3

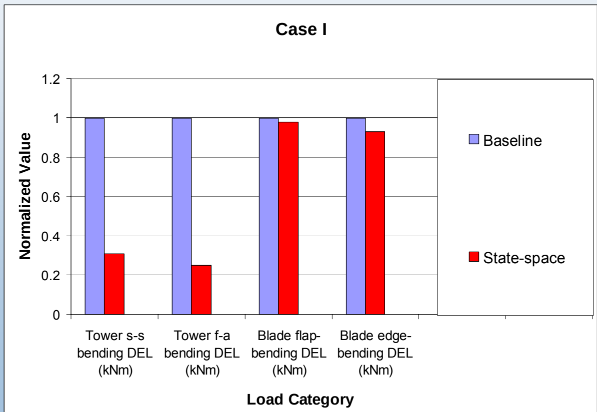


- Significant reduction in most measured loads (**30-70%**)

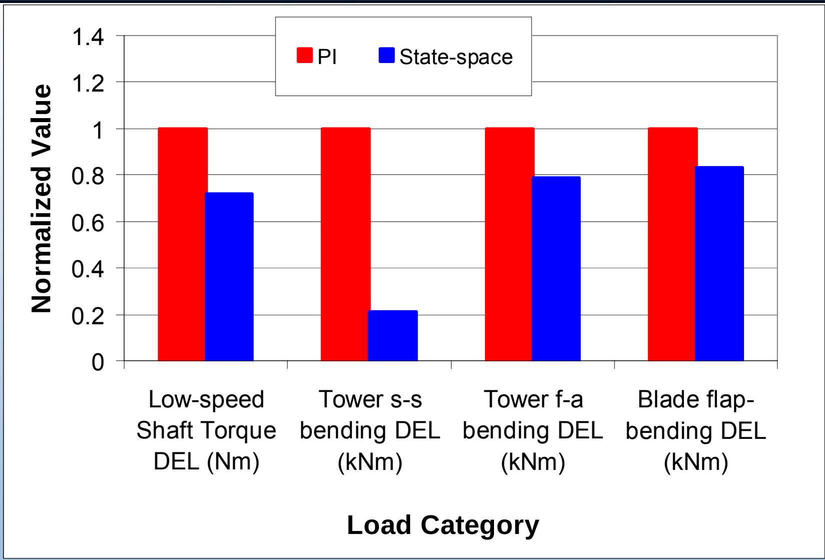
What are we doing now?

- **Develop advanced controls using multiple actuators (blade pitch, generator torque, nacelle yaw, etc.) to reduce loads**
- **Test controls on CART2**
- **Apply controls to commercial machines**

Recent CART2 region 2 tests using generator torque and blade pitch to reduce tower loads



Simulated Control Results – Region 3



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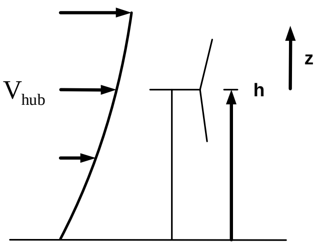
Disturbance Model



$$V(z) = V_{hub}(1 + z/h)^m$$

Fluctuating wind component

$$V(r,\Psi) \cong V_{hub} + V_{hub}\left(\frac{m(m-1)r^2}{4h^2}\right) + V_{hub}\left(\frac{mr}{h}\cos\Psi\right) + hots$$

Uniform wind component

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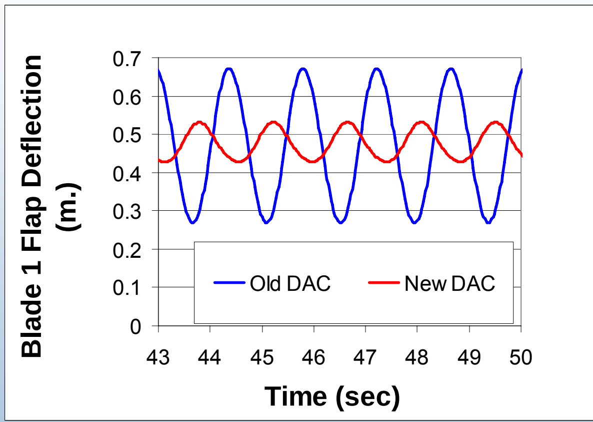
Simulated Control With New Independent Pitch/DAC

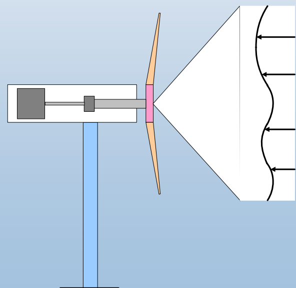


Must measure either tip-deflection or flap-bending moments on each blade

Use of Lidar Measured Wind-speed

- Develop and test controls utilizing advanced look-ahead sensors for load alleviation
- NREL/CU Seed Grant Proposal for start-up work has been awarded ($50-60K)

- Advanced hub-mounted sensor (lidar, sodar, etc.) measures wind profile entering rotor
- Advanced independent pitch controls use information to maximize load alleviation



Conclusions

- Must move away from using old control schemes with multiple loops
- Advanced Controls show great potential for meeting multiple control objectives
  - Stabilizing turbine structure
  - Enhancing energy capture
  - Mitigating dynamic loads
- Will be critical for large flexible machines as well as offshore turbines with many flexible modes

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Plans - Future Work

- Continue advanced controls development and testing – CART3.
- Develop and test advanced independent blade pitch control with look ahead sensor.
- Develop new field testing capability on a large flexible turbine – partner with industry.

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Questions?

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Research Activities on Smart Sensing Technologies in Korea

IEA Wind Topical Expert Meeting on the Application of Smart Structures for Large Wind Turbine Rotor Blades

8-9th May, 2008, Albuquerque

Hyung-Joon Bang
Korea Institute of Energy Research

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Contents

I. Background

II. Manufacturing Process Monitoring

III. In-situ Structural Health Monitoring

- Load Measurement
- Damage Detection

IV. Considerations for FBG installation

V. Conclusion

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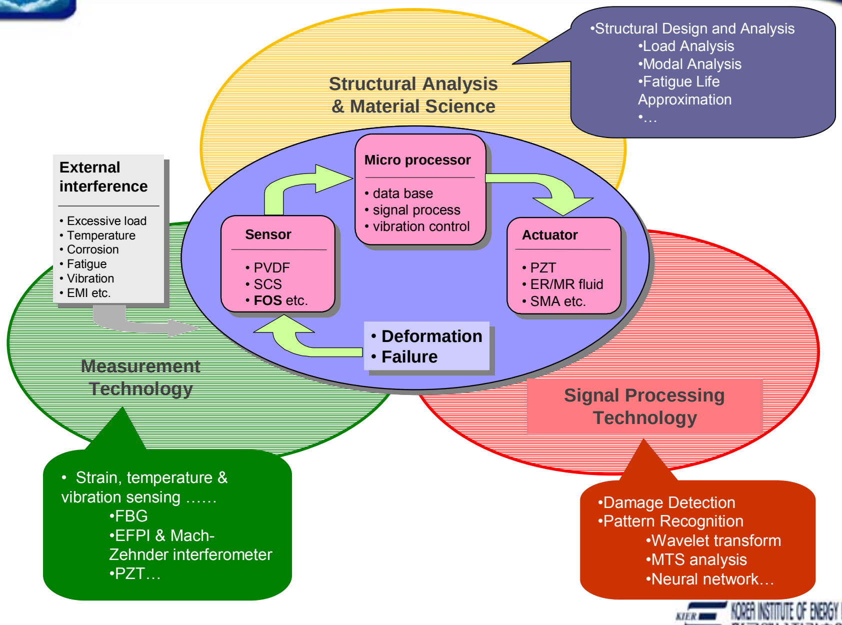
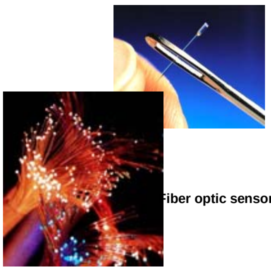
Smart Structures



Fiber Optic Sensors



Fiber optic sensor technology

✓ ***Bragg condition***

$\lambda_B = 2 n_e \Lambda$ n_e : ***effective refractive index*** Λ : ***grating period***

✓ ***Center wavelength shift by external interference***

$\Delta\lambda_B = \lambda_B[(\alpha+\xi)\Delta T + (1-p_e)\Delta\varepsilon]$

Advantages of fiber optic sensors

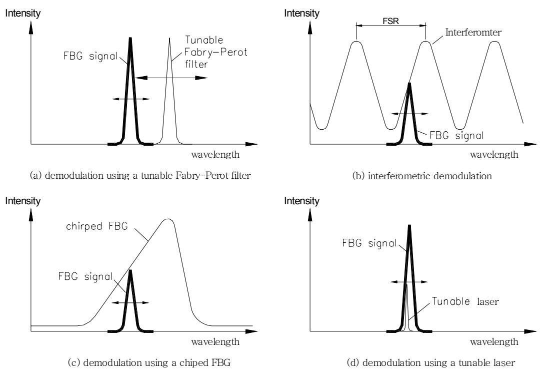
- ✓ no EMI (dielectric material)
- ✓ easy to be embeded into composites
- ✓ flexibility of the sensor size (mm ~ km)
- ✓ wide temperature range (-200 °C ~ 1500 °C)
- ✓ no corrosion in the various environments
- ✓ possible to measure multi-parameters with one sensor

- **Intensity-based fiber optic sensor**
- **Interferometer-type sensor**
- **Fiber Bragg Grating (FBG)**
  - ✓ mass product, multiplexing
  - ✓ can measure various mechanical properties
  - ✓ can be a good counterproposal of conventional sensors for the measurement of strain and temperature

Demodulation Schemes for FBG

1. Direct measurement of Bragg wavelength
- tunable Fabry-Perot filter
- measurement range > 10,000με
- easy multiplexing
- bandwidth < 1kHz

2. Intensity demodulation
- edge filter
- interferometer
- chirped FBG
- tunable laser
- high bandwidth(~MHz), high sensitivity
- measurement range < FSR/2 (~ 200με)



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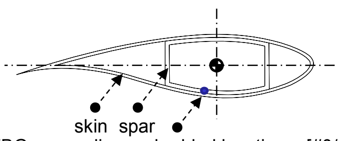
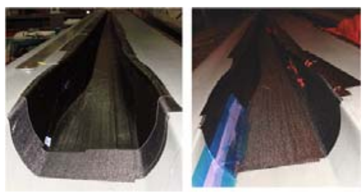
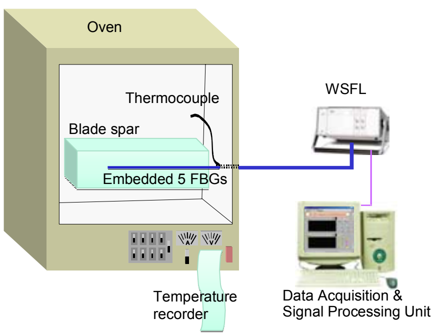
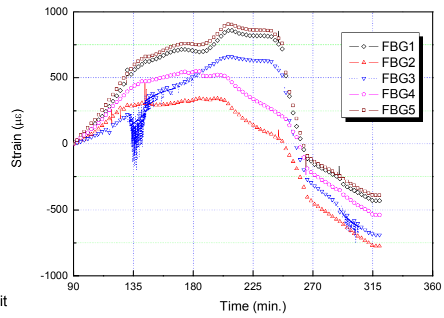
Manufacturing Process Monitoring (I)– Cure monitoring



FBG sensor line embedded location : [#0/0/{FBG}/0₄/#0]T







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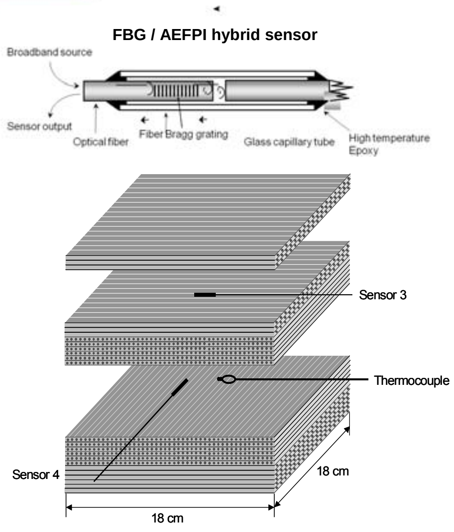
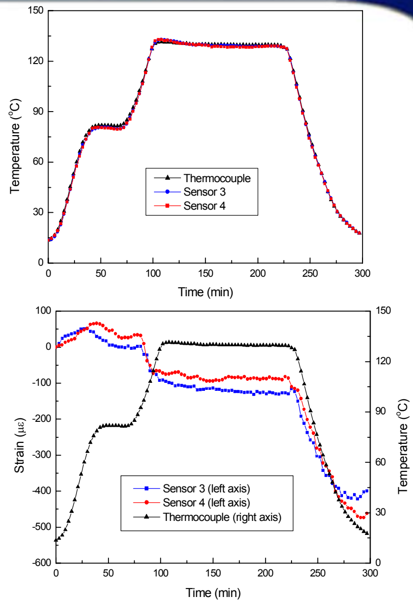
Manufacturing Process Monitoring (II) – Cure monitoring



$[0_6/90_6/\{90\}/90_6/0_3/\{0\}/0_3]_T$



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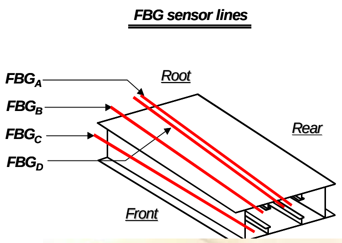
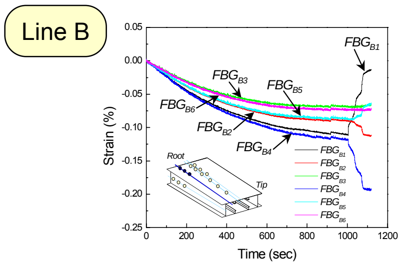
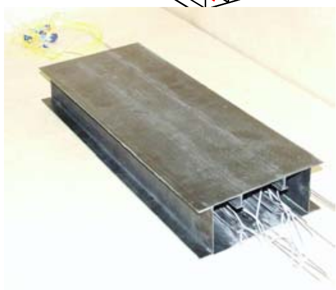
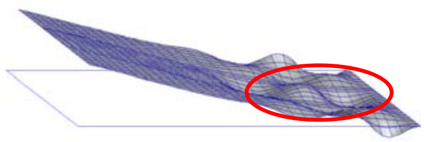
Buckling Monitoring – Embedded FBGs in Wing-box model









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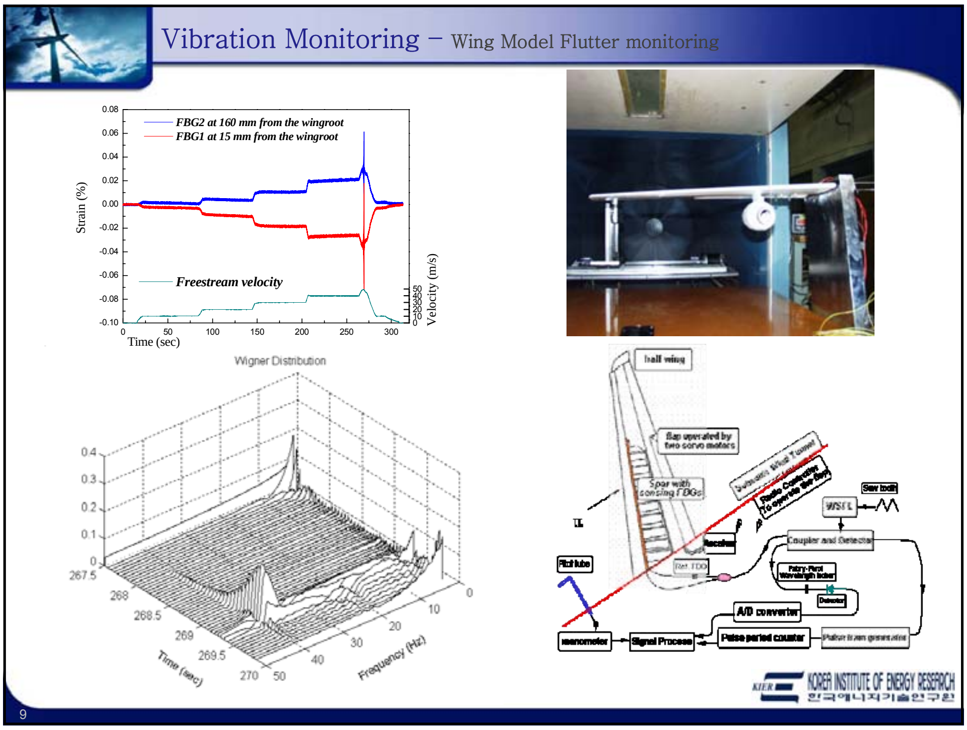
Vibration Monitoring – Wing Model Flutter monitoring
FBG2 at 160 mm from the wingroot
FBG1 at 15 mm from the wingroot
Freestream velocity
Strain (%)
Velocity (m/s)
Time (sec)
Wigner Distribution
Time (sec)
Frequency (Hz)
half wing
flap operated by two servo motors
Spar with sensing FBGs
Receiver
Pitot tube
manometer
Signal Process
Pulse period counter
A/D converter
Coupler and Detector
Detector
WSFL
Saw tooth
Fabry-Perot Wavelength locker
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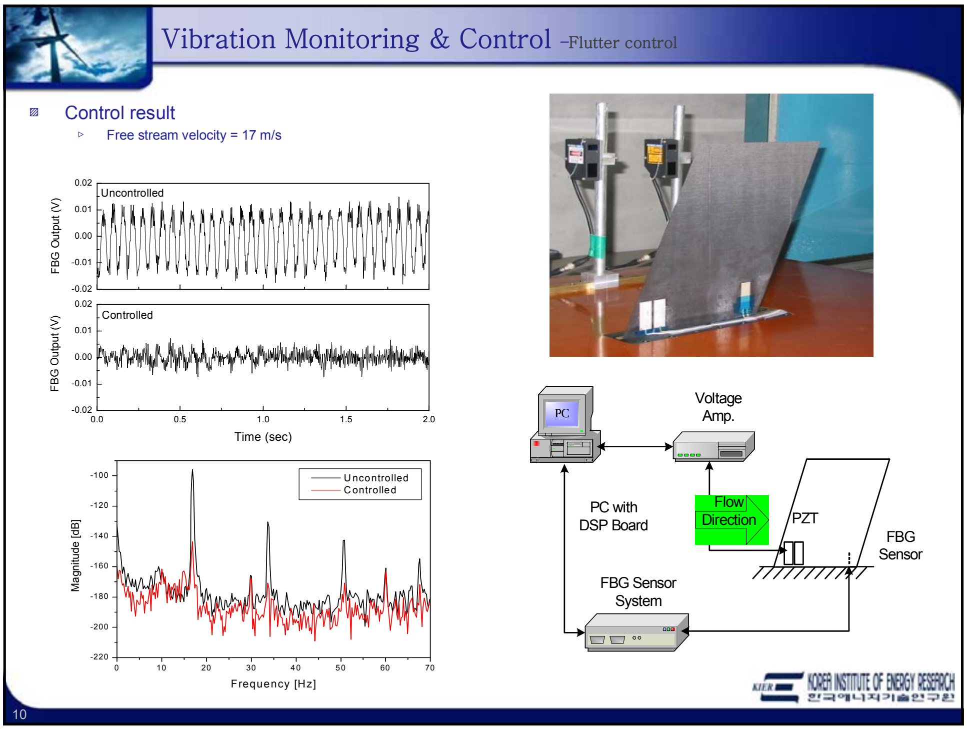
Vibration Monitoring & Control –Flutter control
Control result
Free stream velocity = 17 m/s
Uncontrolled
Controlled
FBG Output (V)
Time (sec)
Uncontrolled
Controlled
Magnitude [dB]
Frequency [Hz]
PC
Voltage Amp.
PC with DSP Board
Flow Direction
PZT
FBG Sensor
FBG Sensor System
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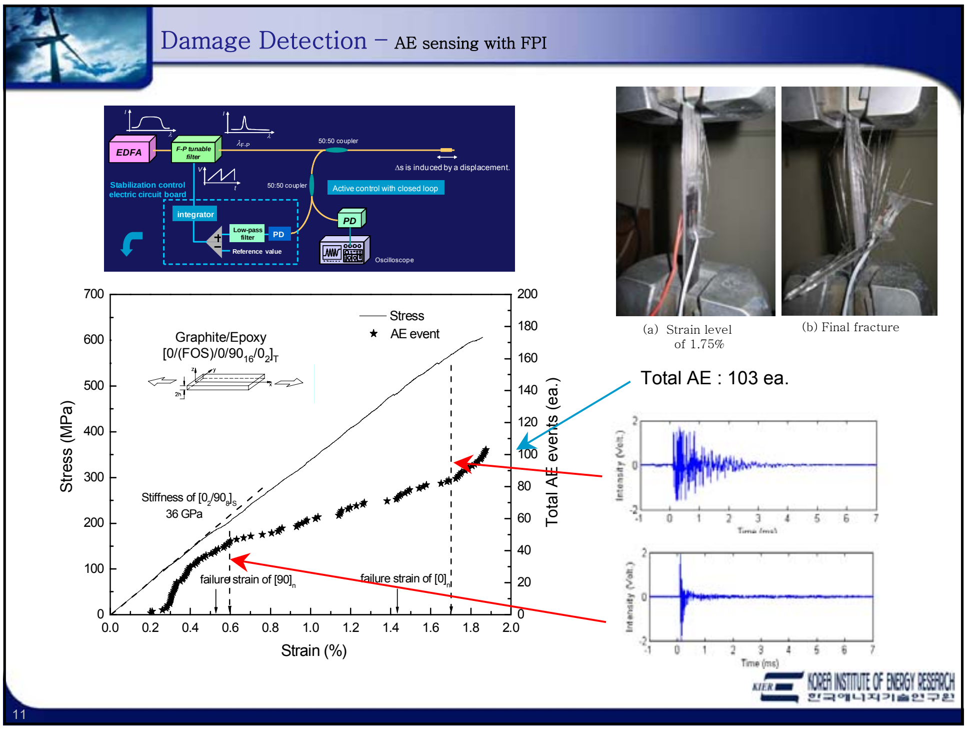
Damage Detection – AE sensing with FPI
EDFA
F-P tunable filter
50:50 coupler
Δs is induced by a displacement.
Stabilization control electric circuit board
Active control with closed loop
Integrator
Low-pass filter
PD
Reference value
Oscilloscope
Graphite/Epoxy
$[0/(FOS)/0/90_{16}/0_2]_T$
Stress
AE event
Stiffness of $[0_2/90]_{8S}$
36 GPa
failure strain of $[90]_n$
failure strain of $[0]_n$
Stress (MPa)
Total AE events (ea.)
Strain (%)
(a) Strain level of 1.75%
(b) Final fracture
Total AE : 103 ea.
Intensity (Volt.)
Time (ms)
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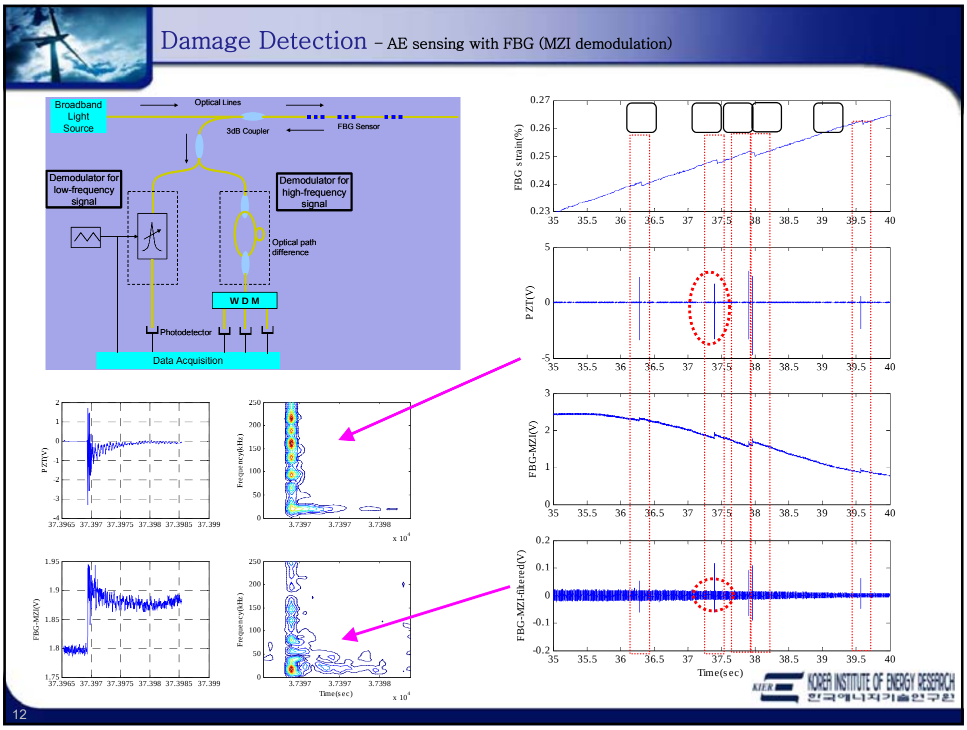
Damage Detection – AE sensing with FBG (MZI demodulation)
Broadband Light Source
Optical Lines
3dB Coupler
FBG Sensor
Demodulator for low-frequency signal
Demodulator for high-frequency signal
Optical path difference
W D M
Photodetector
Data Acquisition
FBG strain(%)
PZT(V)
FBG-MZI(V)
FBG-MZI-filtered(V)
Time(sec)
Frequency(kHz)
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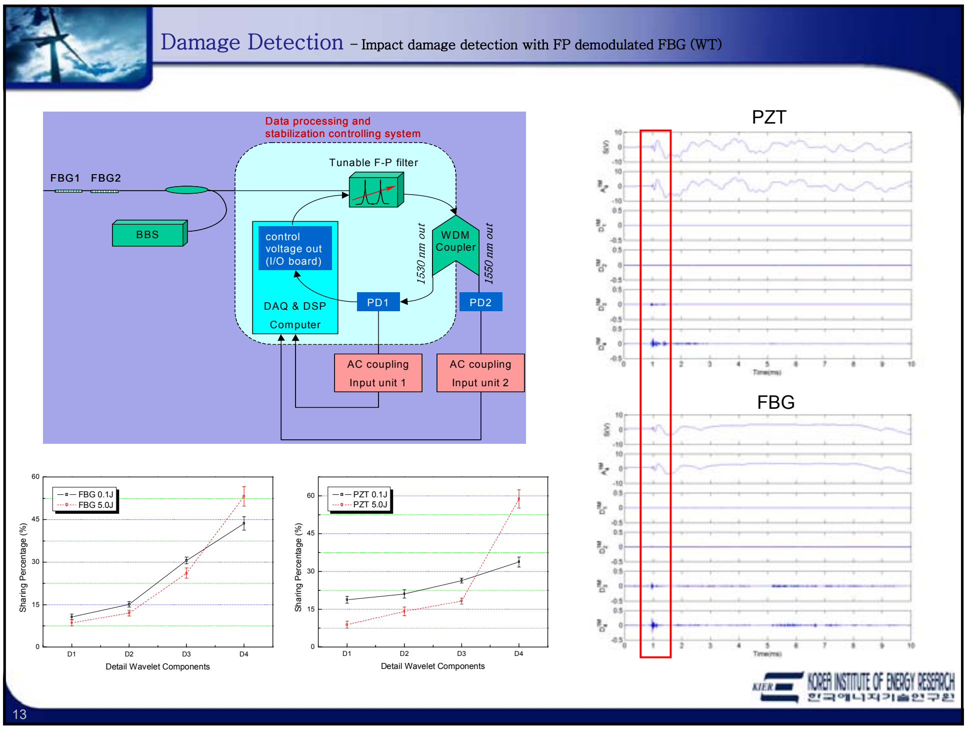
Damage Detection – Impact damage detection with FP demodulated FBG (WT)
Data processing and stabilization controlling system
FBG1 FBG2
BBS
Tunable F-P filter
control voltage out (I/O board)
DAQ & DSP Computer
WDM Coupler
1530 nm out
1550 nm out
PD1
PD2
AC coupling Input unit 1
AC coupling Input unit 2
PZT
FBG
Time(ms)
FBG 0.1J
FBG 5.0J
PZT 0.1J
PZT 5.0J
Sharing Percentage (%)
Detail Wavelet Components
D1
D2
D3
D4
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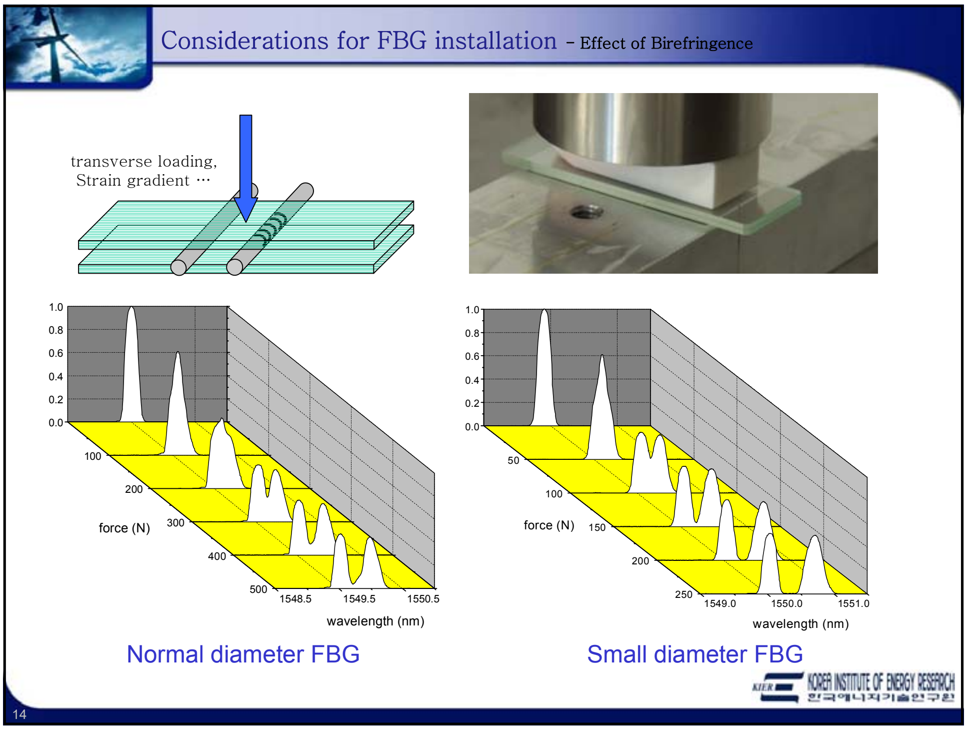
Considerations for FBG installation – Effect of Birefringence
transverse loading,
Strain gradient …
force (N)
wavelength (nm)
1548.5
1549.5
1550.5
1549.0
1550.0
1551.0
Normal diameter FBG
Small diameter FBG
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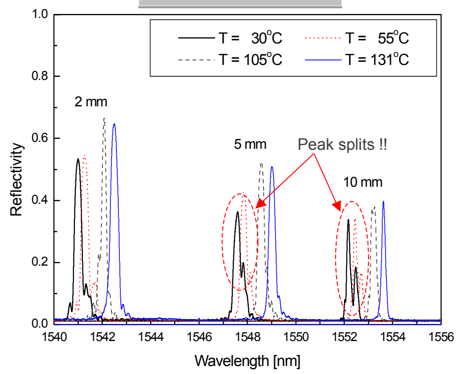
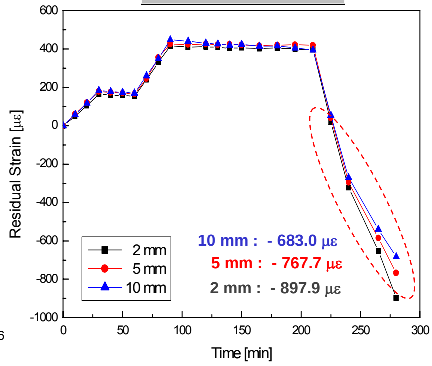
Considerations for FBG installation – Effect of Birefringence

Cool down period



Residual strain



- ✓ During the cool down period, the peak splits occurred
- ✓ In case of 2 mm FBG sensor, peak split did not occur
- ✓ During the cool down period, measurement errors occurred and increased as the temperature decreased

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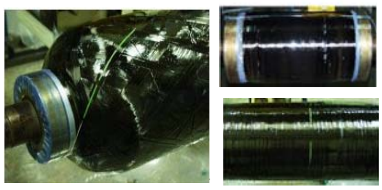
Static Strain Monitoring – Embedded FBGs in Filament Wound Tank

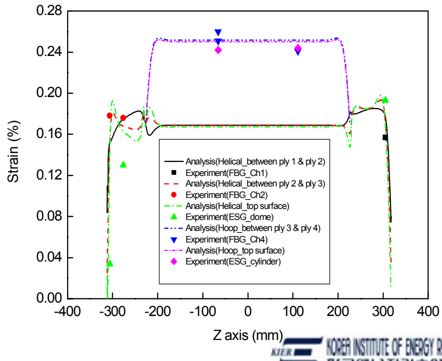


FBG sensor line fabrication process

Process / Content	Previous	Revised
Optical fiber	SMF + hydrogen loading	PSF
Multiplexing	Splicing	Simultaneous fabrication
Reinforcement	Recoat	Recoat + film protect
Ingress/egress	One directional	Bi-directional

- **Water Pressurizing Test**
- **Burst pressure = 3430 psi**

✓ **Cured under rotating condition : 80°C(1hr)→120°C(1hr)→150°C(3hr)**



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Conclusions

- FBG sensors are suitable for structural health monitoring of large composite structures like wind turbine blade.
  - How can these be best used?
  - What needs to be done?
    - Reliability
    - Birefringence

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Active Aerodynamic Blade Control Technology for Large Wind Turbines

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dwilso@sandia.gov

Rush D. Robinett, III, Dale E. Berg, Don W. Lobitz, Jose R. Zayas
Energy & Infrastructure Future/Wind Energy Technology
Sandia National Laboratories

Invitation to Topical Expert Meeting #56 on
THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR BLADES
IEA RD&D Wind, Task 11
Sandia National Laboratories
Albuquerque, NM
May 8-9, 2008

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Problem Statement & Goal

- With Wind Turbines Blades Getting Larger and Heavier, Can the Rotor Weight be Reduced by Adding Active Devices?
- Can Active Control be Used to Reduce Fatigue Loads?
- Can Energy Capture in Low Wind Conditions be Improved?

Initial Research Goal:

Understand the Implications and Benefits of Embedded Active Blade Control, Used to Alleviate High Frequency Dynamics

Research Objectives

- Define the active aero control problem (critical path /drivers, analysis/simulation scenario, performance index: maximize energy capture, minimize root moment, other)
- Proof-of-concept (i.e., microtab control to reduce fatigue loads/cycling)
- Preliminary Technical Approach:
  - Optimization for tab on/off sequencing
  - Conventional feedback control for reducing load/fatigue in turbulent case
  - Dynamic stall flutter problem analysis w/ nonlinear power flow limit cycle control proof-of-concept

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Active AeroDynamic Blade Control Technology R&D

Work plan incorporates:

- Trailing edge devices (microtabs, trailing edge flaps w/ smart structures, etc.)
- Morphing wing concept
- Wind tunnel testing
- Field testing (proof-of-concept)
- Transition to industry

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Future Control Design to Reduce Load/Fatigue & Improve Energy Capture

- Lightweight adaptive blade design with embedded sensors and actuators with variable pitch
- Combined blade pitch/flap control system (reduced loading above rated speed, increased energy capture below rated speed)
- Nonlinear flutter control system identifies stability boundary, improved performance by promoting lightweight/high strength blade design
- Individual pitch control system (reduces fatigue loading) also incorporated

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Active Flow/Load Control

- Active Load Control:
  - May remove fundamental design constraints for large benefits
  - These large benefits are feasible if active control technology is considered from the onset
  - May allow for lighter more slender blade designs
- Active Load Control has Already been Implemented in Wind Turbine Design. e.g.:
  - Yaw control
  - Blade pitch control
  - Blade aileron (Zond 750)

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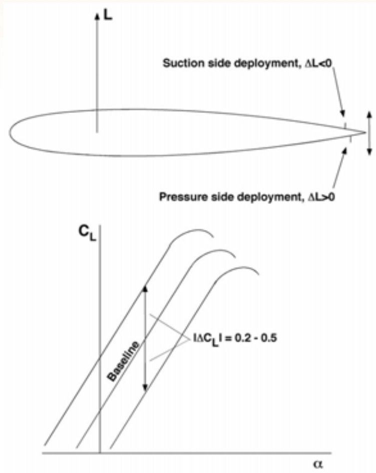
Microtab Concept

- Evolutionary Development of Gurney flap
- Tab Near Trailing Edge Deploys Normal to Surface
- Deployment Height on the Order of the Boundary Layer Thickness
- Effectively Changes Sectional Camber and Modifies Trailing Edge Flow Development (so-called Kutta condition)

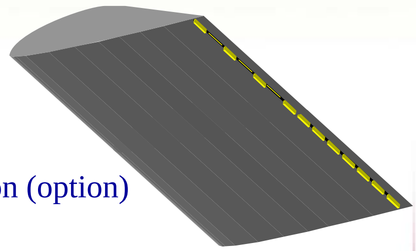


Collaboration: Case van Dam at UC Davis

Sandia National Laboratories

Microtab Concept

- Small, Simple, Fast Response
- Retractable and Controllable
- Lightweight, Inexpensive
- Two-Position “ON-OFF” Actuation (option)
- Low Power Consumption
- No Hinge Moments
- Expansion Possibilities (scalability)
- Do Not Require Significant Changes to Conventional Lifting Surface Design (i.e., manufacturing or materials)

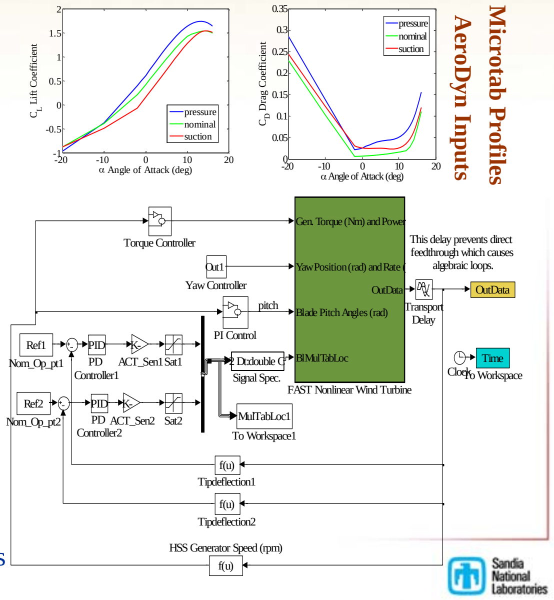


Collaboration: Case van Dam at UC Davis

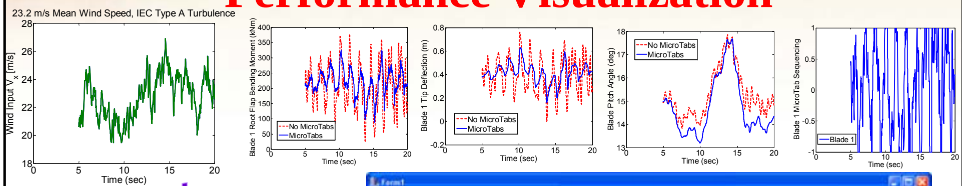
Sandia National Laboratories

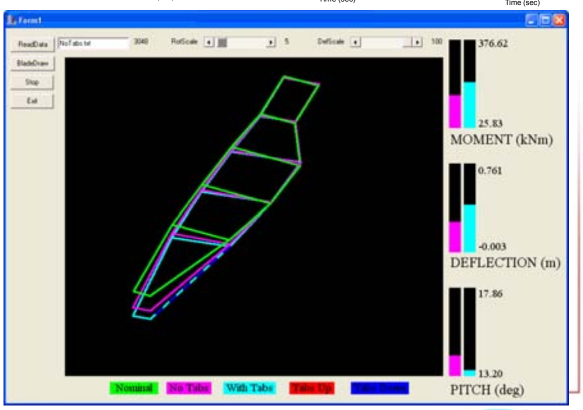
System Modeling - Analysis

- **Controls Advanced Research Turbine (CART):** utilized as simulation testbed with 600kW rated power @ 42 RPM
- **Dynamic Simulation Environment:** FAST (Fatigue, Aerodynamics, Structures, and Turbulence) run within Matlab/Simulink
- **Hybrid Controller:** Proportional-Integral (PI) Blade Pitch Control with Proportional-Derivative (PD) Microtab Control for above rated wind speed conditions, Region III
- **Microtab PD Control:** Uses tip deflection feedback and nominal reference tip deflection as set point



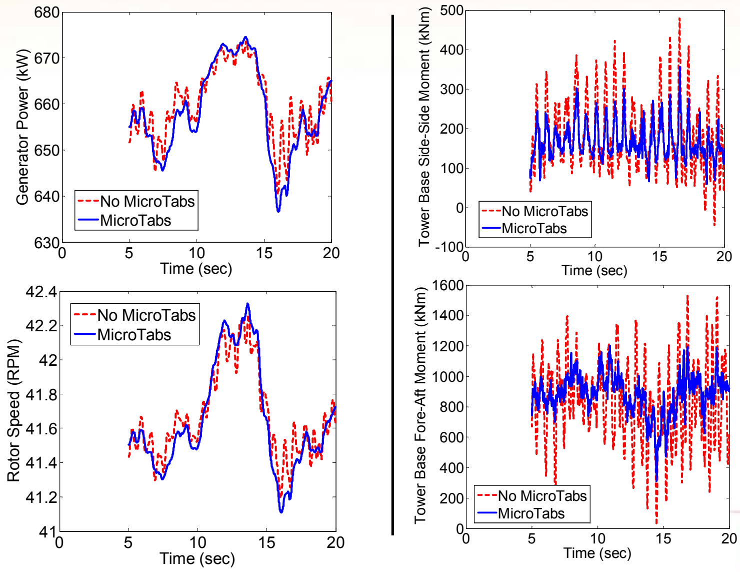
Microtab Active Aero Blade Control Performance Visualization



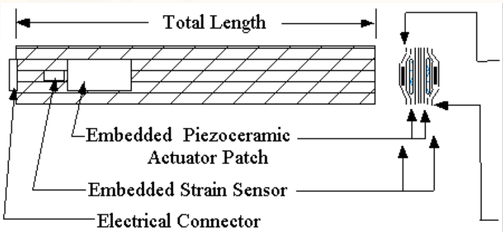


Region III

Reduction in High Frequency Oscillations Tower Base Moments Reduced



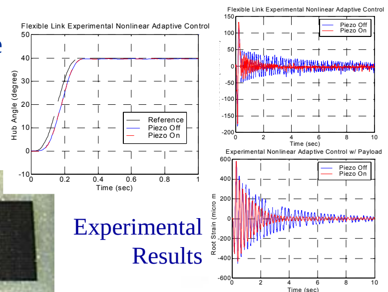
Composite Smart Link Design for Active Slewing Structures (Previous Work)



Ply #	Angle
1	45
2	0
3	0
4	-45
5	45
6	0
7	0
8	-45

Actuator Patch

Graphite/Epoxy Composite Link with embedded strain sensor and piezoceramic actuator patch



Experimental Results

Ref: D.G. Wilson, **Nonlinear/Adaptive Control Architectures with Active Structures for Flexible Manipulators**, PhD Dissertation, Mechanical Engineering, University of New Mexico, May 2000

Lyapunov Optimal, Hamiltonian, and Exergy/Entropy Thermodynamics

- General Exergy Rate Equation

$$\dot{\Xi} = \sum_i \left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i + \sum_j \left(\dot{W}_j - p_o \frac{dV}{dt}\right) + \sum_k \dot{m}_k \xi_k^{flow} - T_o \dot{S}_i$$

- The link between: "Lyapunov optimal"; the "Hamiltonian"; and exergy/entropy thermodynamics is defined as

$$\dot{V} = \dot{H} = \dot{W} - T_o \dot{S}_i = \sum_{j=1}^{N} Q_j \dot{q}_j - \sum_{l=N+1}^{M+N} Q_l \dot{q}_l$$

- Subject to the following necessary and sufficient conditions:
- $T_o \dot{S}_i \geq 0$ Positive semi-definite, always true
- $\dot{W} \geq 0$ Positive semi-definite – Exergy pumped into system

Nonlinear Power Flow Control Design: Stability/Performance: Class of Nonlinear Systems

Power terms are sorted into three categories (for linear systems: point-by-point cancellation) over a cycle:

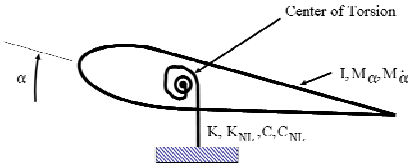
Power Generators	$\left(Q_j \dot{q}_j\right)_{ave} > 0$	$(\dot{W})_{ave}$
Power Dissipators	$\left(Q_l \dot{q}_l\right)_{ave} < 0$	$\left(T_o \dot{S}_i\right)_{ave}$
Reversible/Conservative Exergy/Storage Terms	$\left(Q_k \dot{q}_k\right)_{ave} = 0$	$\left(T_o \dot{S}_{rev}\right)_{ave}$

Ref1: R.D. Robinett, III and D.G. Wilson, **What is a Limit Cycle?,** *International Journal of Control*, Accepted for Publication, Jan. 2008.

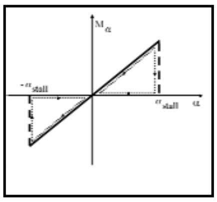
Ref2: R.D. Robinett, III and D.G. Wilson, **Exergy and Irreversible Entropy Thermodynamic Concepts for Nonlinear Control Design**, *International Journal of Exergy*, Accepted for Publication, Feb. 2008.

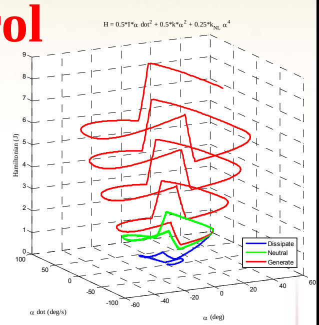
Nonlinear Systems (Flutter) Limit Cycle Control

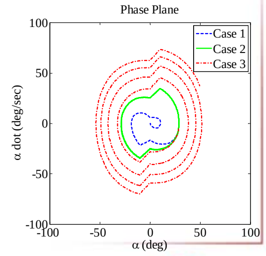
- **Nonlinear Power Flow Control Design: Dynamic Stall: Limit Cycle Identification**

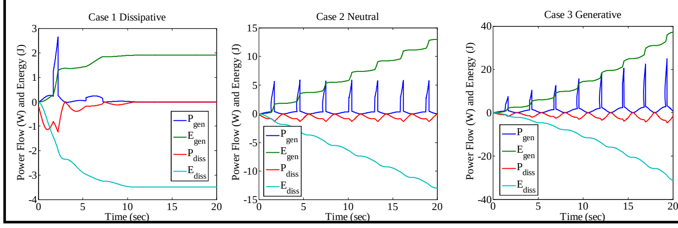


NL Dynamic Stall characteristics









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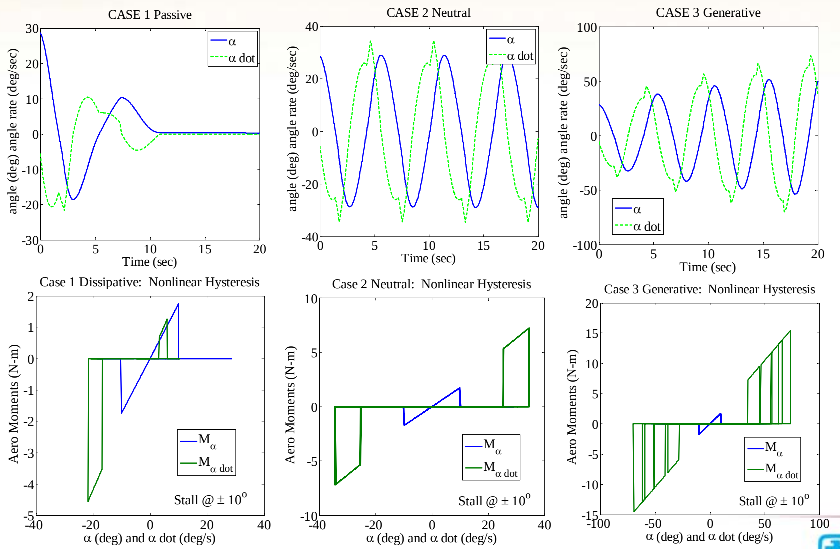
Future NL Power Flow Controls Based on Physics: Characterize and Control Blades



Responses

Aero Moments

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Observations - Summary

- **Potential Benefits to Designer:**
  - **Increase Effective Rotor Size**
  - **Extend Potential Life Expectancy and Reliability**
  - **Ultimately Reduce Cost-Of-Energy of Future Large Wind Turbine Machines**
- **Active Aero Devices may Provide Substantial Benefit for Future Wind Turbine Designs**
- **Advanced Nonlinear Power Flow Control Design Incorporates Dynamic Stall Flutter ID and steps toward Intelligent Control**
- **Smart Structures with Embedded Sensors and Actuators: Candidate for Smart Blade Design and Development**

Sandia National Laboratories

Acknowledgments

- **UC Davis**
  - Professor Case van Dam
  - M. Leal
  - J.P. Baker
- **Sandia National Laboratories**
  - Jeffery J. Carlson
  - Tom Ashwill

Sandia National Laboratories

Thank you … Questions?

- **Further Info -**

- **AWEA Conference:**

D.G. Wilson, D.E. Berg, D.W. Lobitz, and J.R. Zayas, **Optimized Active Aerodynamic Blade Control for Load Alleviation on Large Wind Turbines,** AWEA, WindPower 2008, Houston, Texas, June 1-4, 2008.

- **Workshop Proposal Submitted:**

R.D Robinett, III and D.G. Wilson, **Nonlinear Power Flow Control Design:** *Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis***,** IEEE Conference on Decision and Control, Cancun, Mexico, December 8, 2008.

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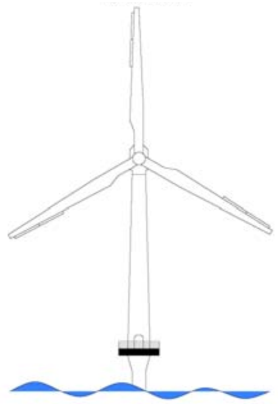
On the proof of concept of a `Smart' rotor using a traditional controller design cycle

Expert meeting 2008:
Jan-Willem van Wingerden
Teun Hulskamp
Thanasis Barlas
Gijs van Kuik
Michel Verhaegen



Delft Center for Systems and Control

Delft University of Technology

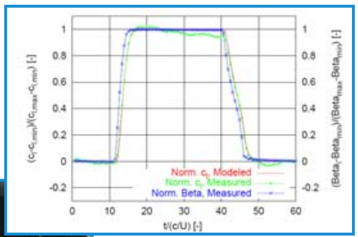
Outline

- Introduction
- Experimental design
- Modeling
- Controller design
- Experimental results
- Challenges for control
- Conclusions

Introduction

First feasibility study performed by Risø:

- 2D experiment
- Lift measurements
- Stiff blade
- No feedback control



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Introduction

Next step feasibility study of a non rotating 'blade' :

- 3D experiments
- Load measurements
- Flexible blade
- Real time feedback control

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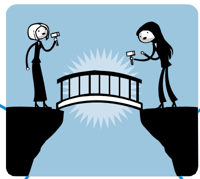
Introduction

This presentation:

On the proof of concept of a `Smart' rotor using a traditional controller design cycle

Modeling → Validation → Controller design → Validation



Wind community

Control community

Experimental design

- Wind tunnel
- Blade
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system

- Low speed (< 120 m/s)
- Low turbulence
- Cross section (b x h x l)
  1.8 x 1.25 x 2.6 m
- No direct possibilities do generate
  (known) dynamic disturbances

Experimental design

- Wind tunnel
- **Blade**
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system

- Dynamic scaling
  (reduced frequency)
- Constant aerodynamic profile
  (no twist, no taper)

$$k = \frac{\omega_k c}{2V_k}$$

	Reference turbine	Experimental model
Chord [m]	1.8	0.12
Characteristic velocity [m/s]	54	45
1P load [Hz]	0.28	3.5
3P load [Hz]	0.84	10.5
1^{st} flapping mode [Hz]	1	12.5

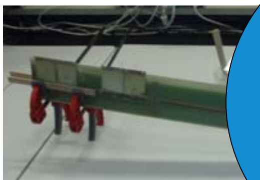
Scaling of the dynamic properties based on the 75% blade length values

Experimental design

- Wind tunnel
- **Blade**
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system

- 3 sections

DU-W96-180



1 m

For more information about the mechanical design check the presentation of Teun Hulskamp

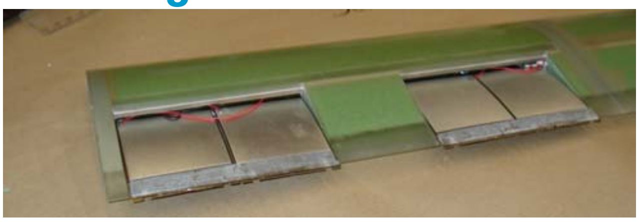
Experimental design

- Wind tunnel
- Blade
- **Pitch system**
- Trailing edge flap
- Sensors
- Real-time system

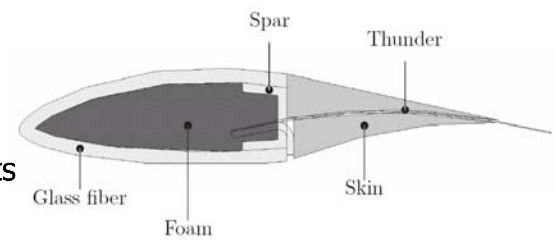
- Goal: to mimic disturbances
- High power linear force actuator
  (with position measurement)
- Designed our own feedback controller

Experimental design

- Wind tunnel
- Blade
- Pitch system
- **Trailing edge flap**
- Sensors
- Real-time system



- Flexible trailing edge flap
- Piezo bender (Thunder)
- High voltage requirements



Experimental design

- Wind tunnel
- Blade
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system

Without wind

Experimental design

- Wind tunnel
- Blade
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system

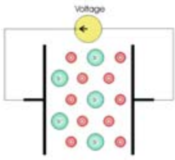
With wind:

Observe aeroelastic coupling

Experimental design

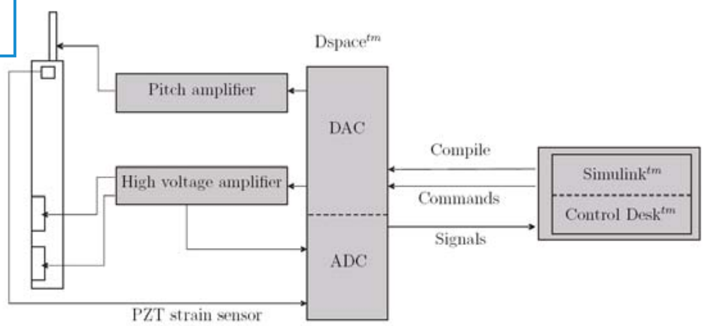
- Wind tunnel
- Blade
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system

- 2 PZT sensors in the root



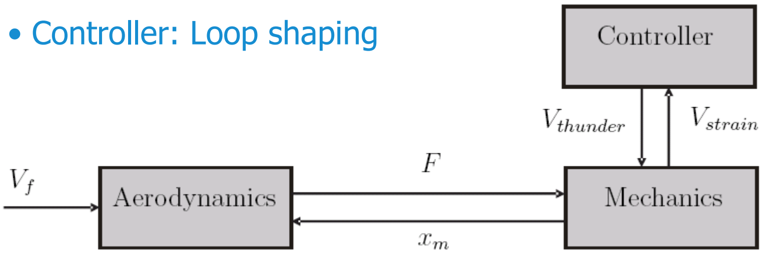
Experimental design

- Wind tunnel
- Blade
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system



Modeling: First principles

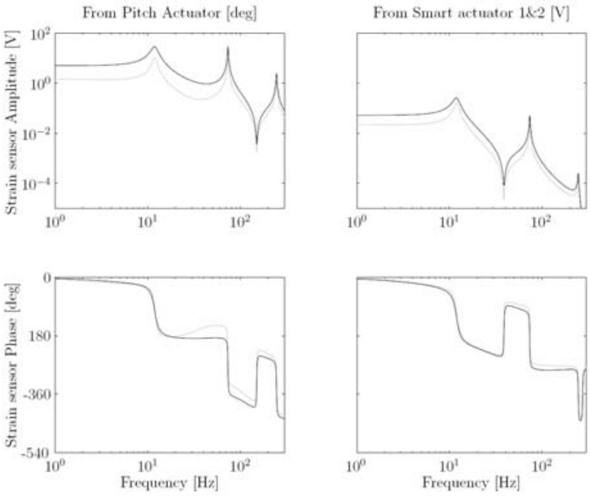
- Two port model
- Aerodynamics: Theodorsen
- Mechanics: Multi-body
- Controller: Loop shaping



Modeling: First principles

Bode plot

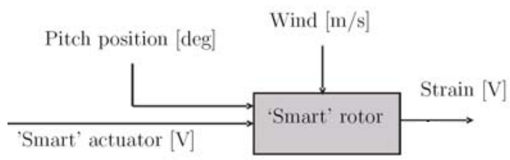
- For 45 m/s black
- For 30 m/s grey



Modeling: Experimental modeling

Experimental modeling

- Large uncertainties in First Principles model
- All the dynamics present in I/O data is modeled
- Subspace identification



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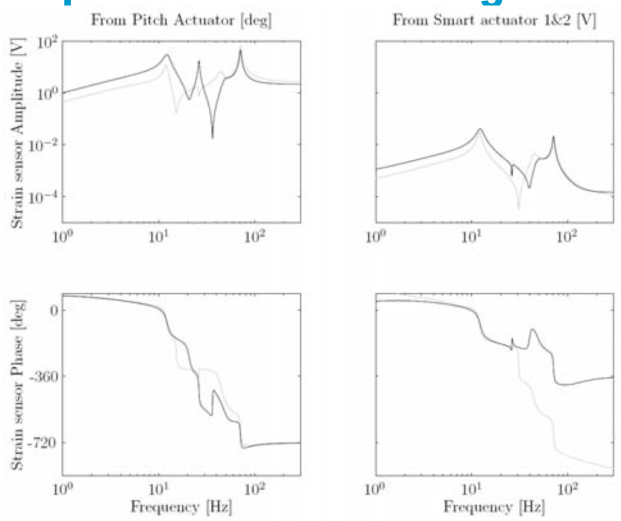
Modeling: Experimental modeling

Bode plot

- For 45 m/s black
- For 30 m/s grey
- 10th order model



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Modeling: Validation

Quality of the identified model

- VAF:

$$\mathrm{VAF} = \max\left\{1 - \frac{\mathrm{var}(y - \hat{y})}{\mathrm{var}(y)}, 0\right\} * 100\%$$

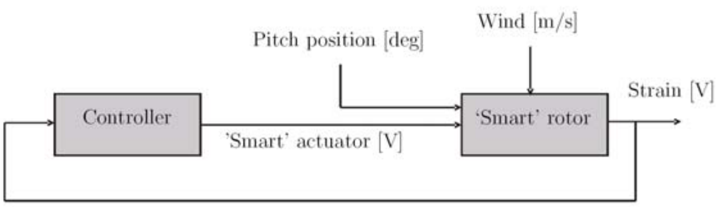
The Variance Account For (VAF) for the different models

V [m/s]	θ[deg]	VAF PZT [%]
30	3	85.2
30	6	86.2
45	3	89.5
45	6	91.6

Controller design

Loop shaping

- SISO
- Lack of robustness in LQG
- Low order controller: PD with notch and additional roll-off



Experimental results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

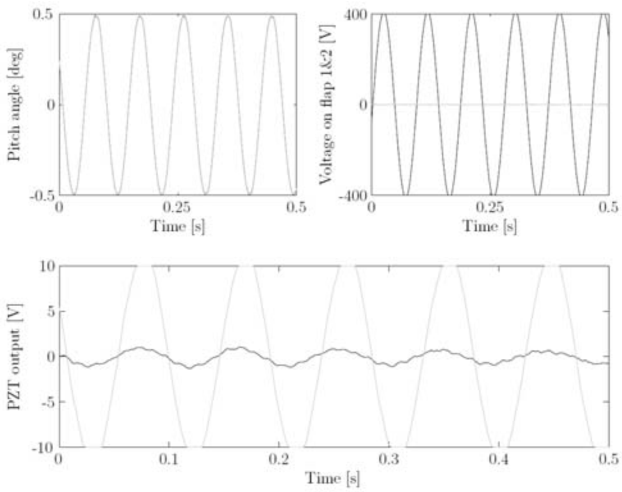
Experimental results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

V= 30 m/s

α= 6 degrees

3P excitation



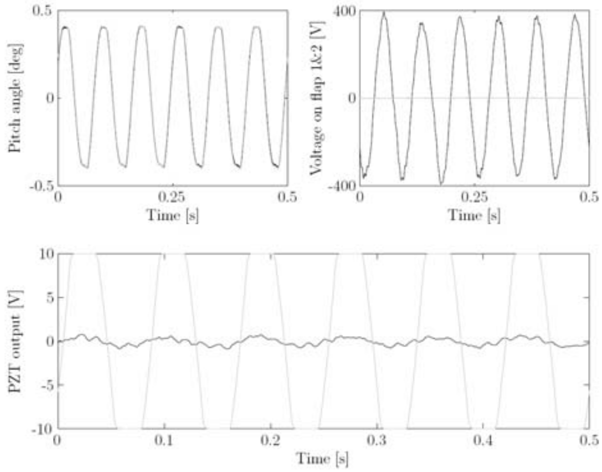
Experimental results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

V= 30 m/s

α= 6 degrees

Eigenfrequency



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Experimental results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

V= 30 m/s

α= 6 degrees

Eigenfrequency flap excitation

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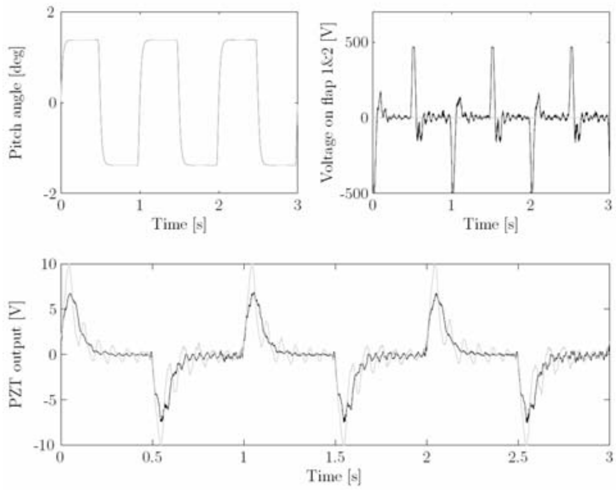
Experimental results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

V= 30 m/s

α= 6 degrees



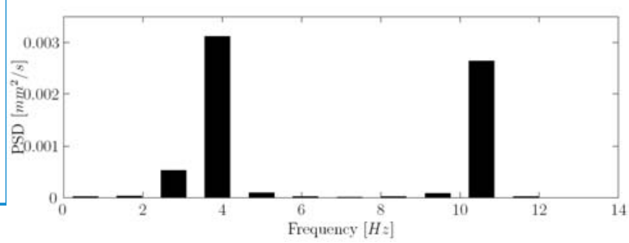
Experimental results

Input spectrum

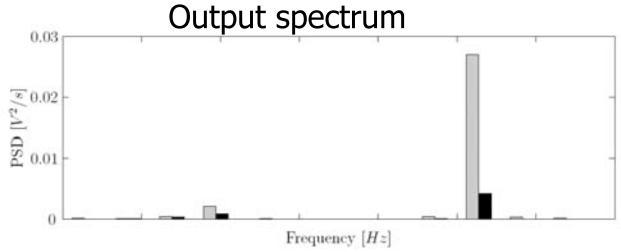
- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

V= 30 m/s

α= 6 degrees



Output spectrum



Challenges: Rotating 'Smart' blades

Next step to show the feasibility: Rotating `Smart' blades

- Two blades
- Multiple actuators and sensors

Challenges:

-Real-time MIMO control (H2, Hinf, data-driven control)

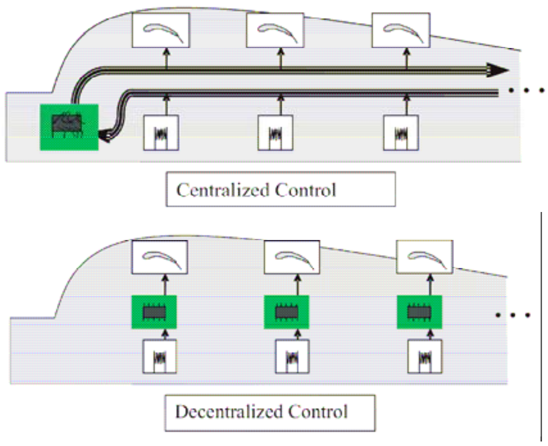
-Periodic components (2 blades)

Challenges: Distributed control

Control for distributed systems

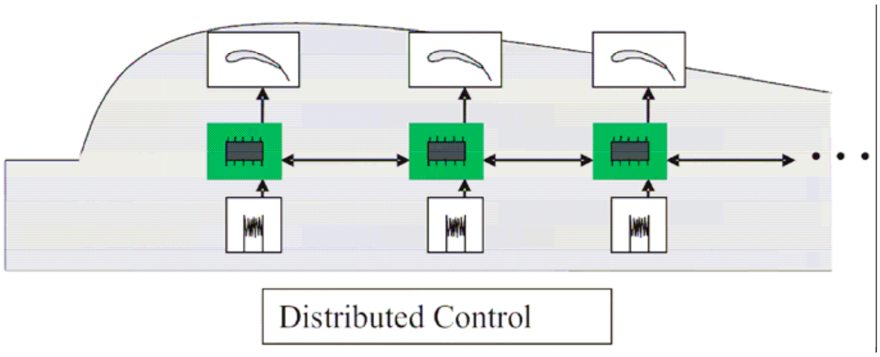
- Large number of actuators and sensors
- Centralized vs Decentralized control

•Or….



Rice

Challenges: Distributed control



Rice

Conclusions

- We showed the next step in the proof of concept of a 'Smart' rotor
- We showed the effectiveness of the controller design cycle
- We highlighted a number of challenges from a control point of view

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Overview of Active Load Control R&D

C.P. (Case) van Dam

IEA RD&D Wind, Task 11

The Application of Smart Structures for Large Wind Turbine Rotor Blades

8-9 May 2008

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Acknowledgments

- Wind Technology Department, Sandia National Laboratories, Albuquerque
- Lawrence Livermore National Laboratory
- Past & present graduate students at University of California, Davis:
  - Jonathan Baker
  - Raymond Chow (National Defense Science and Engineering Graduate Fellowship)
  - Aubryn Cooperman
  - Scott Johnson
  - Edward Mayda
  - Dora Yen Nakafuji
  - Kevin Standish
  - Seung Yeun Yoo
  - Et al

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Presentation Outline

- Background and motivation
- Methodologies
  – CFD
  – Wind tunnel
  – Structural dynamics simulations
- Current efforts
  – Automated airfoil aerodynamic performance table generator
  – Wind tunnel model development
- Concluding remarks

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Active Load Control

- Goal is to evaluate active load control for turbine blades and its impact on cost of energy
- Aerodynamic loading on blade can be modified through:
  – Blade incidence angle
  – Flow velocity
  – Blade size
  – Blade aerodynamic characteristics
- Focus is on small fast-acting systems that change sectional aerodynamic characteristics to alleviate load spikes due to gusts and to reduce blade tip deflections during high load conditions

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Blade Load Control Techniques

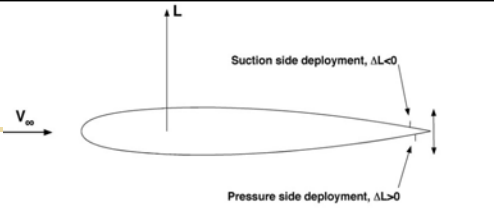
- Techniques to control blade loads and rotor performance:
  - Blade size (variable blade length)
  - Incidence angle (variable pitch)
  - Airspeed (variable speed)
  - Section aerodynamic characteristics
- In future we will consider the control of all of these simultaneously

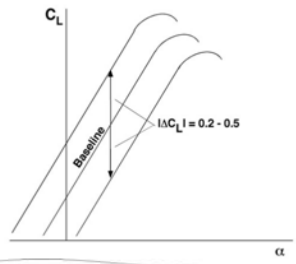
$$L = \int_{r=0}^{R} \left[c_{\ell_\alpha} \left(\alpha + \theta_{pitch} - \alpha_o\right) \tfrac{1}{2}\rho \left\{ V_{wind}^{2} + \left(2\pi n r\right)^{2} \right\} c \right] dr$$

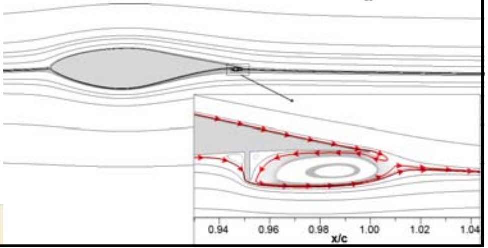
- Goal is to evaluate active load control for turbine blades and its impact on cost of energy
- Focus is on small fast-acting systems that change sectional aerodynamic characteristics to alleviate load spikes due to gusts and to reduce blade tip deflections during high load conditions

Microtab Concept

- Conceptualized in 1998
- Tabs that deploy (near-)normal to flow direction
- Forward of the trailing edge
  - Upper or lower surface
- Hinge-less device
  - Small actuation forces
- h_{tab} ~ boundary layer thickness
- Trailing-edge flow condition is altered







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Microtab Deployment

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

Microtab Deployment

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

Methodologies

- CFD
- Wind Tunnel
- Structural Dynamics Simulations

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Motivation: CFD

- CFD allows in-depth study of the effect of small devices on:
  - Sectional lift, drag, pitching moment
  - Transient force and moment during tab deployment
  - 3D blade performance and loads
- Reynolds number effect is evaluated with CFD
- CFD is used to rapidly generate airfoil tables for baseline/tabbed/flapped blade sections. These tables are critical for rotor performance and structural dynamic analysis

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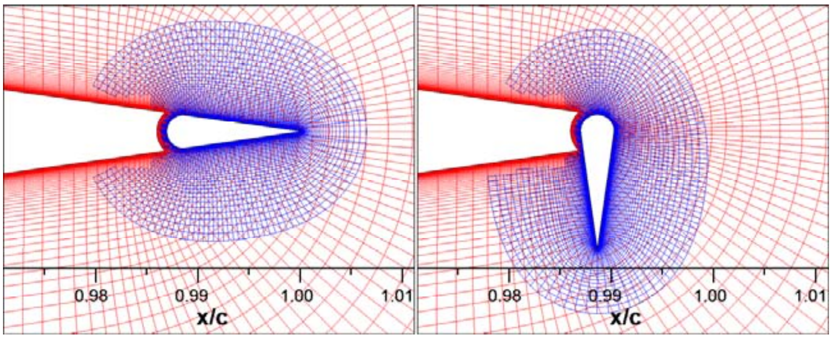
Trailing-Edge Mesh Detail - Microflap

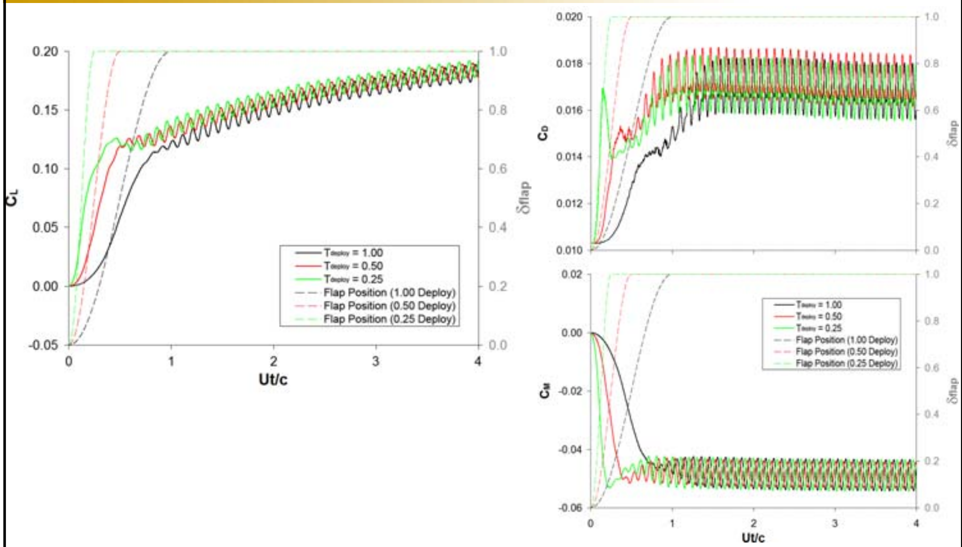
Body-fitted O-grid



Rectracted | Fully deployed

Microflap Deployment Time Effect

NACA 0012, $\alpha = 0^{\circ}$, Re = 1.0×10^6, Ma = 0.25



Motivation: Wind Tunnel

- Wind tunnel provides final check on numerical simulations before moving ahead with full-scale development
- For wind energy, testing is mostly 2D
  - Baseline airfoils
  - Airfoil with trailing edge devices
  - Impact of premature transition
- Questions were raised about the effectiveness on a three-dimensional wind turbine blade
- Tunnel size limitations allow only for a wind turbine blade tip model
- Focus of devices in blade tip region (region where load control devices are most effective)

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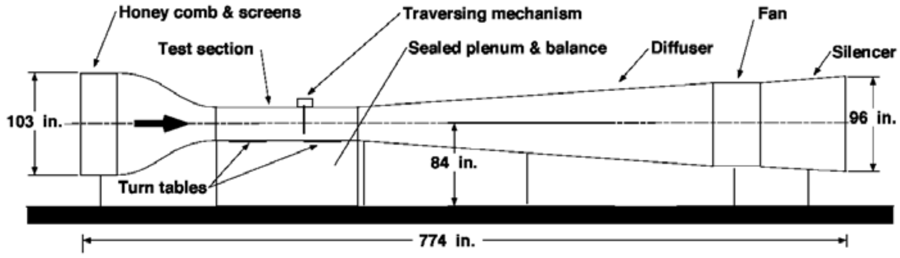
Methods: Wind Tunnel



- Open circuit, low subsonic
- Test section dimensions
  - Cross section: 0.86 m x 1.22 m (2.8 ft x 4 ft)
  - Length: 3.66 m (12 ft)
- Low turbulence < 0.1% FS for 80% of test section

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Motivation: Structural Dynamics Simulations

- Conduct aeroelastic simulations of complete turbine with load control devices to investigate the load mitigating capabilities of devices
- Allows evaluation of effectiveness under a variety of wind loading scenarios
- Aeroelastic simulations conducted using FAST/Aerodyn software with MATLAB's Simulink
- Methodology applied to demonstrate effectiveness of microtabs in controlling blade tip clearance

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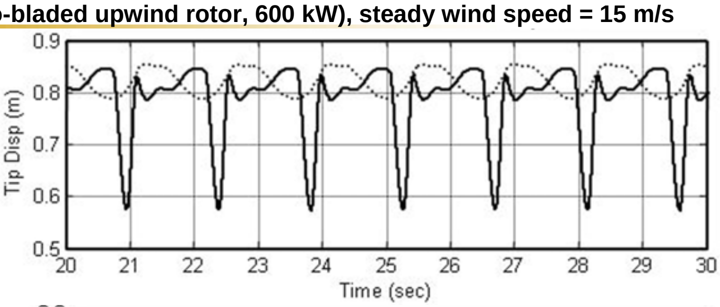
Effect of Tabs on Tip Displacement

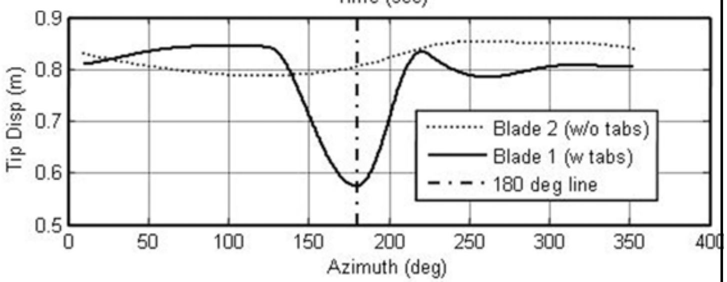
NREL CART (two-bladed upwind rotor, 600 kW), steady wind speed = 15 m/s

Tip displacement as function of time. Tabs activated just before blade reaches tower (azimuth angle = 180 deg) and retracted after passing tower



Tip displacement as function of azimuth angle

Note: smaller blade tip displacement indicates larger tower clearance



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Source: D. Lobitz, Sandia

Automated Airfoil Aerodynamic Performance Table Generator

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Goal

- To develop an automated tool for generating sectional aerodynamic force and moment data with minimal amount of user input
  - Automated Grid Generator
  - Automated Flow Solver
    - Based on AutoFS code developed by E. Mayda
    - US Patent 7,124,038 by van Dam, Mayda, Strawn

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Automated Grid Generator

- Design Goals:
  - Starting with airfoil X-Y coordinates
  - Simple inclusive input file
    - Hands off mesh generation process
    - Default parameters for every option
    - Default override capability for more advanced users
    - Geometry modifications
  - RANS quality mesh

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Mesh Generation Capability

- Ability to create both C- and O-grid
- Surface smoothing and redistribution
- User specified Reynolds number
  - Wall spacing customization for various turbulence models
- TE gap detection and closure
- Multiple wake cut options
  - Wake smoothing
  - Wake angle
- Multiple smoothing parameter defaults

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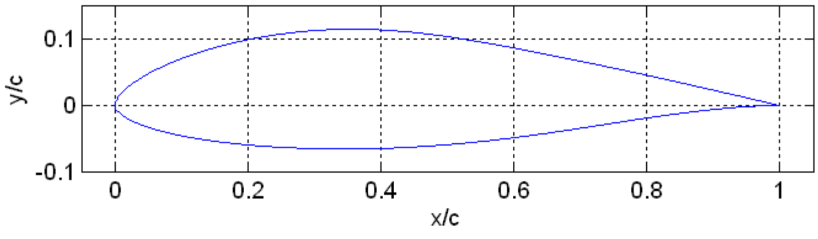
Geometry Modification

- Blunt trailing edge
  - Added thickness
- Plain flap
  - Hinge location
  - Deflection angle
- Microtab
  - Tab location, thickness, height
  - Upper/Lower surface placement

Automated Grid Generator: Example

- Unmodified DU96-W-180 Airfoil



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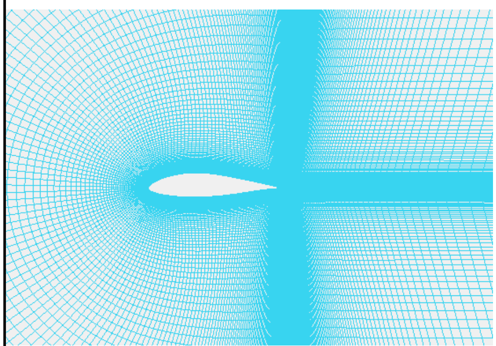
Example: Unmodified DU96-W-180

- User Specification
  - Coordinates: DU96.dat
  - Grid output file: DU96grid.in
  - C-Mesh
  - 201 Surface points
  - Reynolds Number 1,000,000
  - LE Spacing = 1E-3
  - TE Spacing = 5E-4
  - No Geometry Modification
- Input File

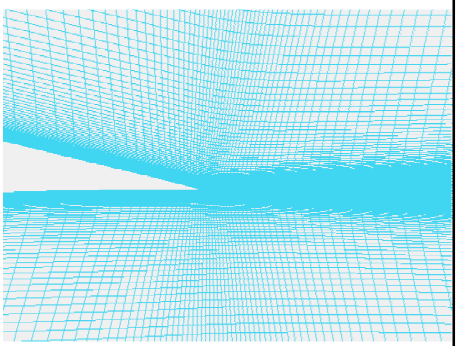
```
-i      DU96.dat
-o      DU96grid.in
-mode   0
-p      201
-r      1000000
-le     0.0010
-te     0.0005
```


Example: Unmodified DU96-W-180

Grid generated:



C-GRID



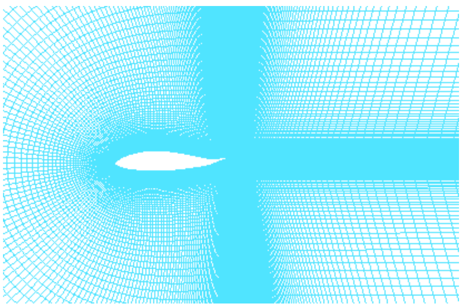
TRAILING EDGE REGION

Example: DU96-W-180 with Plain Flap

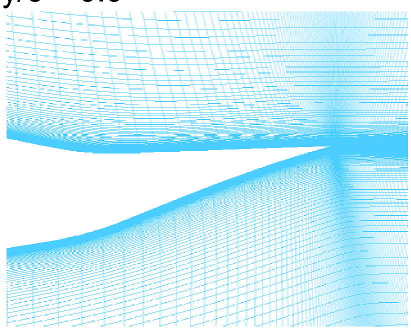
User Specification	Input File	
Coordinates: DU96.dat	-i	DU96.dat
Grid output file, DU96grid.in	-o	DU96grid.in
C-Mesh	-mode	0
201 Surface points	-p	201
Reynolds Number 1,000,000	-r	1000000
LE Spacing = 1E-3	-le	0.0010
TE Spacing = 5E-4	-te	0.0005
Plain Flap	-flap	1
X-Hinge Location x/c = 0.8	-xf	0.8
Y-Hinge Location at y/c = 0.0	-yf	0
Flap Deflection Angle = -15°	-def	-15

Example: DU96-W-180 with Plain Flap

- Flap setting
  - Deflection angle = -15°
  - Hinge location at x/c = 0.8, y/c = 0.0



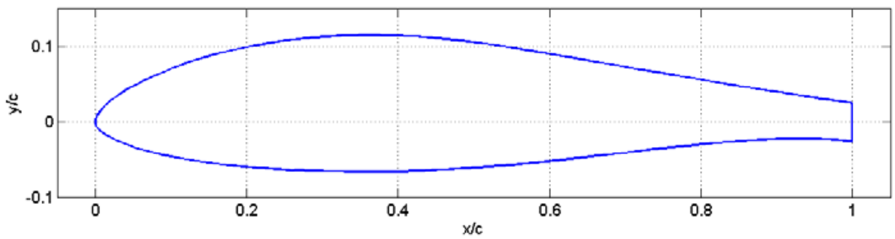
C-GRID



TRAILING EDGE REGION

Example: DU96-W-180 with Blunt TE

- Geometry modification
  - Blunt Trailing Edge
    - 5.0%*c* thickness



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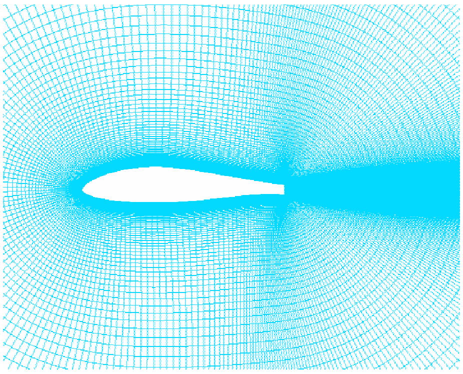
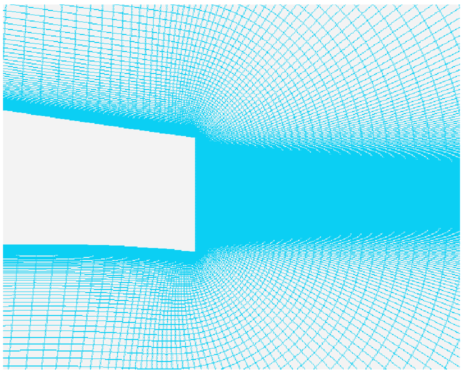
Example: DU96-W-180 with Blunt TE

Grid:



O-GRID



TRAILING EDGE REGION

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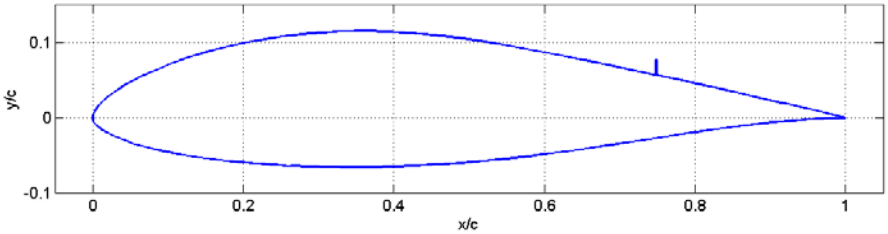
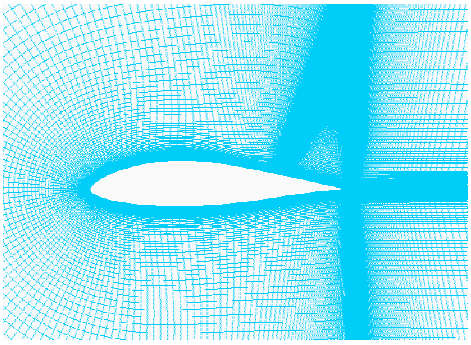
Example: DU96-W-180 with Tab

- Geometry modification
  - Microtab
    - X/c = 0.75, 2%*c* tab height, 0.2%*c* tab width

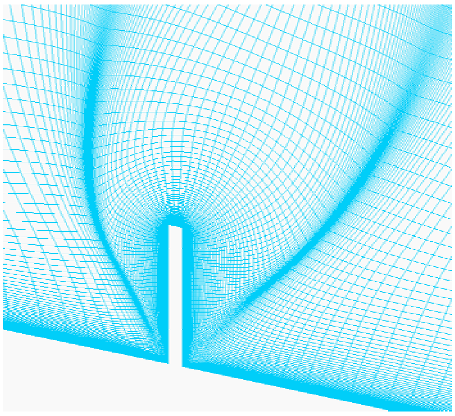


Example: DU96-W-180 with Tab

Grid:



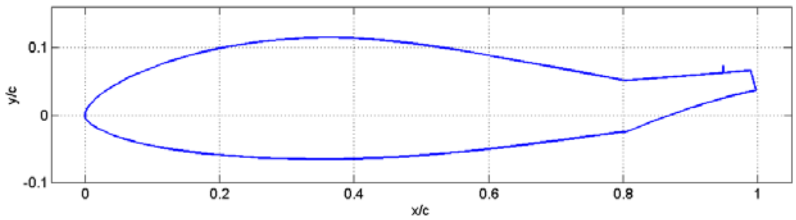
C-GRID



MICROTAB REGION

Example: DU96-W-180, Multiple Mods

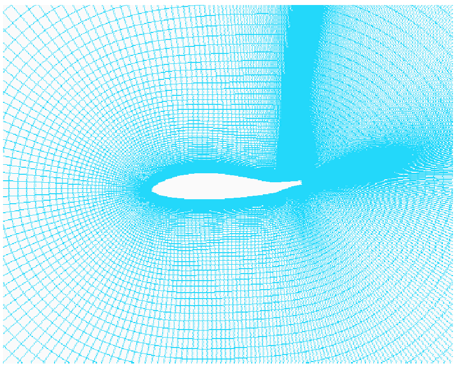
- Geometry modification
  - Plain Flap
    - Hinge point at (x/c = 0.8, y/c = 0.0)
    - Deflection angle = -15˚
  - Microtab
    - x/c = 0.75, 2.0%*c* tab height, 0.2%*c* tab width
  - Blunt Trailing Edge
    - 3.0%*c* thickness



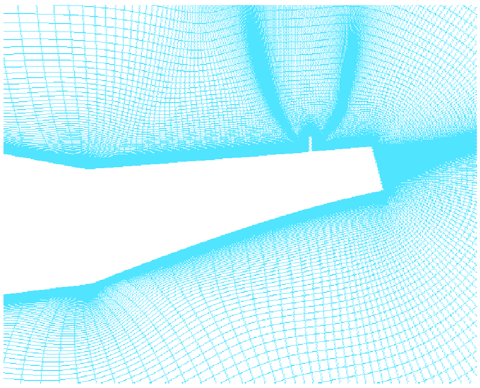
UCDAVIS COLLEGE OF ENGINEERING

Example: DU96-W-180, Multiple Mods

Grid generated:



O-GRID

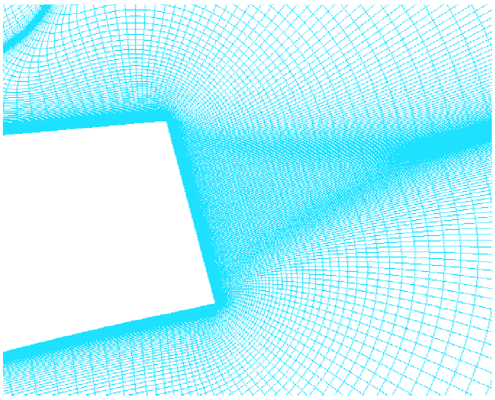


TRAILING EDGE REGION

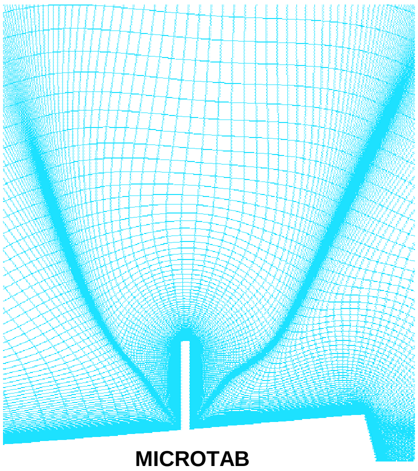
UCDAVIS COLLEGE OF ENGINEERING

Example: DU96-W-180, Multiple Mods

Grid generated: Detailed View



BLUNT TE REGION



MICROTAB REGION

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Automated Flow Solver

- Design Goals:
  - Hands off airfoil performance table generation
    - Full range of angle of attack: -180° to +180°
  - Simple text input file
  - FAST format output file
  - Relatively short turn-around time

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Flow Solver

- ARC2D
  - Reynolds-averaged Navier-Stokes flow solver
  - Spalart/Almaras turbulence model
  - Two calculation modes
    - Steady-state
    - Time-accurate
  - Multiple numerical schemes
  - Mesh sequencing
  - Calculation restart capability

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Flow Solver Automation Features

- Multiple calculation models
  - Steady-state (SS)
  - Time-accurate (TA)
  - Mixed mode: SS → TA
- CFL-number, time-step modulation
- Restart option for incomplete solution
- Divergent solution detection
- Convergent solution detection
  - Moving-average algorithm
  - Correlation analysis

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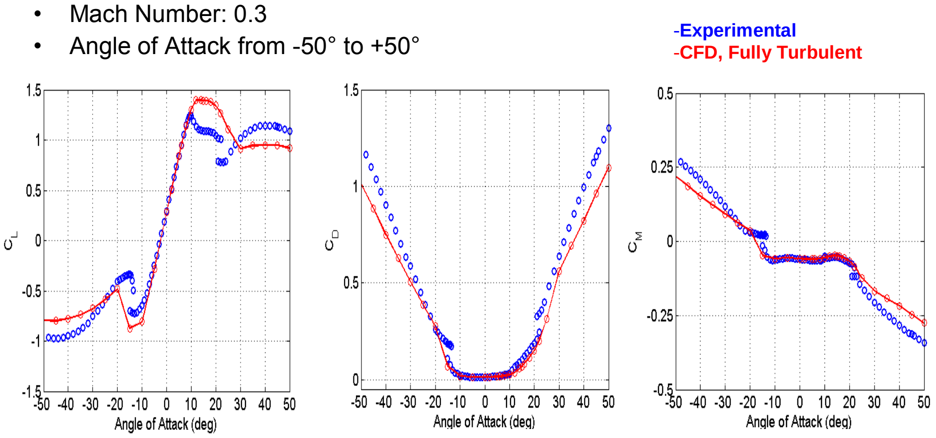
Example: DU96-W-180 Airfoil

- Reynolds Number
  - Experimental Re = 700,000
  - CFD Re = 1,000,000
- Mach Number: 0.3
- Angle of Attack from -50° to +50°



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Mechanical Design of the Microtab-Based Load Control System

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Goal

- Design, manufacture, and test microtab aerodynamic load control system
  - Actuation system will be fully contained within the airfoil model
    - Last 30% chord is a reasonable goal
  - Numerous tabs lining both pressure and suction side of model
    - Fully controllable (Individual and sets of tabs)
  - Wind tunnel testing can include steady and unsteady cases with this design

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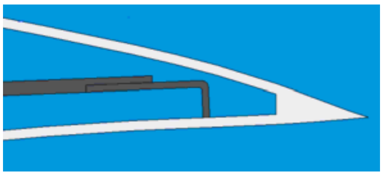
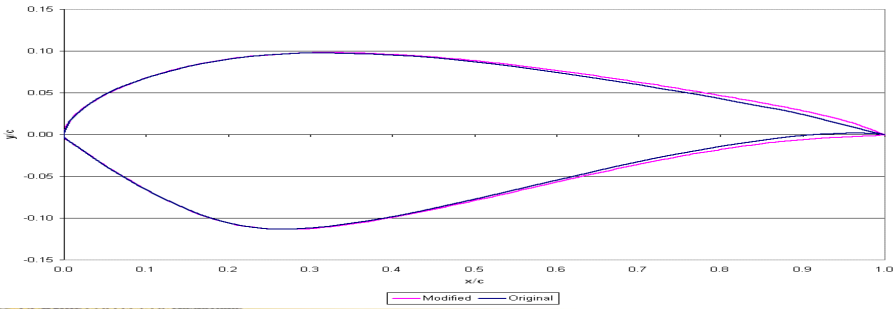
Modified S819 Airfoil

- Minor modifications needed to allow room for retracted tab
- Thickness at 95% chord was doubled.





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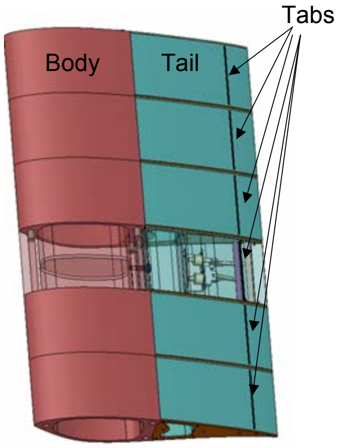
Wind Tunnel Model Design

- 18-in. chord
- 33-in. span for 2D wind tunnel testing
- Tabs line both upper and lower surface
  - Maintains a 90% Solidity Ratio
- Unique airfoil design
  - Detachable design:
    - Main body & trailing-edge tail section
      - Baseline modified airfoil
      - Different actuation systems and designs (microtab, microflap, etc.)
  - Modular design
    - Span split into 6 bays
      - Actuator system installation
      - Structural ribs between tabs
      - Contain air leakage in individual bay

Complete Model



Source:
Maglio Inc. & UC Davis

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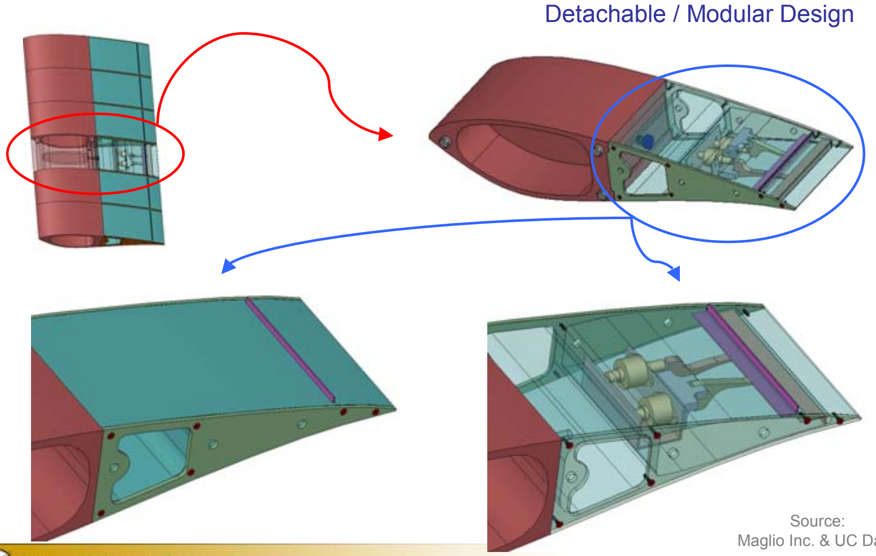
Wind Tunnel Model Design

Detachable / Modular Design



Source:
Maglio Inc. & UC Davis

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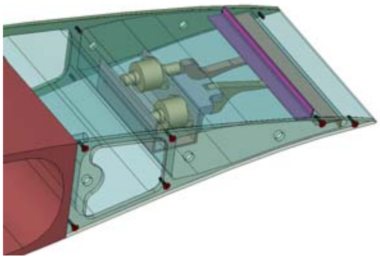
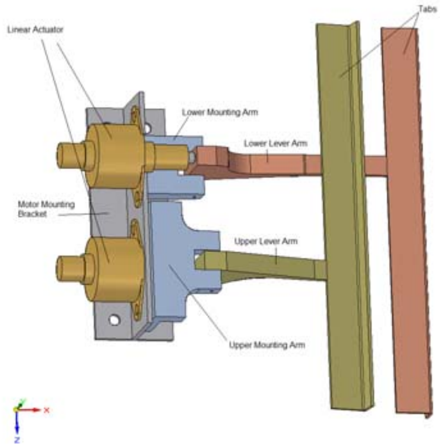
Wind Tunnel Model Design

Actuation System





Source:
Maglio Inc. & UC Davis

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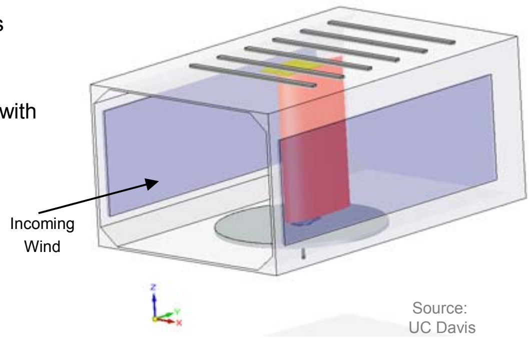
Wind Tunnel Model Design

Wind Tunnel Testing

- Testing configurations
  - Baseline airfoil
    - Force balance
    - Static pressure transducers
  - Tabbed airfoil
    - Static pressure transducers
    - Dynamic fast-pressure transducers
    - Vary incoming wind speed with tab control algorithm

CAD model of wind tunnel test section



Source:
UC Davis

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Concluding Remarks

- Multi-prong effort to RD&D aerodynamic load control system for wind turbine blades
- Fast force response times show the promise of an effective small tab- or flap-based load-control system
- Small tabs and flaps show similar transient behavior
- Computational fluid dynamics continues to play a critical role in the research and development of this blade load control concept
- Extensive wind tunnel testing has verified the effectiveness of the concept
- Aeroelastic simulations of the effect of the tabs in conjunction with a simple control algorithm demonstrate favorable impact on blade tip deflections

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Materials Research and Smart Blades

Sandia 2008 Smart Blade Workshop

May 8-9, 2008

R.P.L. Nijssen

T. Westphal

E. Stammes

TU Delft

Knowledge Centre WMC
Wind turbine Materials and Constructions

Wind turbine Materials & Constructions

- History
  - Blade & Material testing for over 20 years
  - Part of Delft University of Technology
- Activities
  - Full-scale wind turbine structural testing
  - Material research
  - Software Development
- Facilities
  - Flexible full-scale test laboratory
  - Fatigue test machines
  - Workshops
  - Specimen production
- Projects (EZ/EU)
  - OPTIMAT
  - INNWIND
  - UPWIND

TU Delft

Knowledge Centre WMC
Wind turbine Materials and Constructions

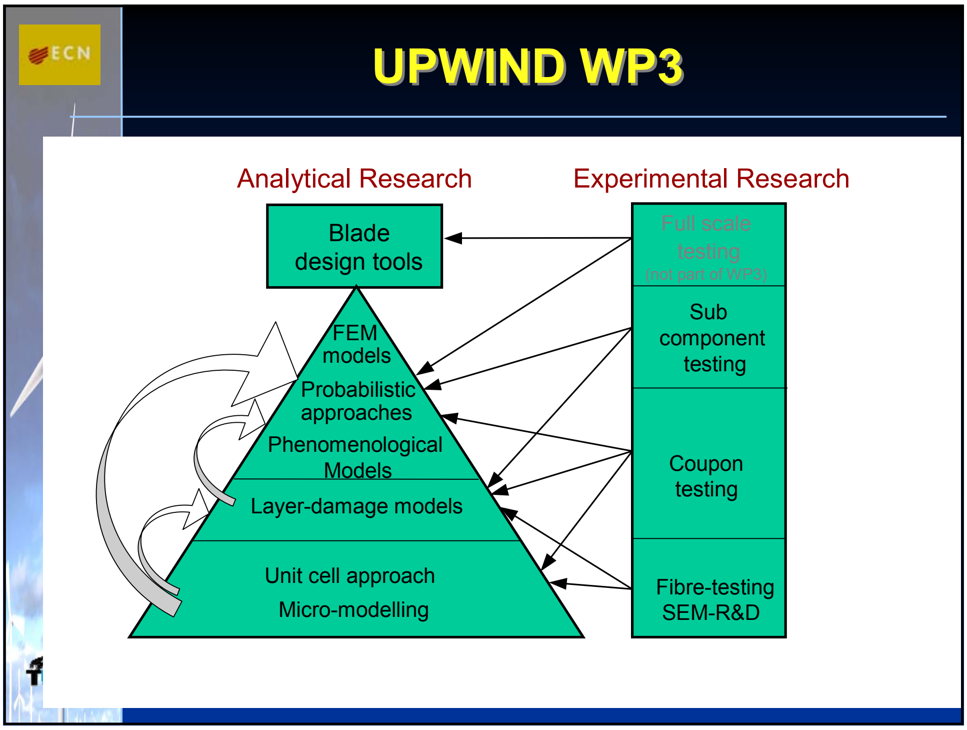
Material Research

Knowledge Centre WMC
Wind turbine Materials and Constructions

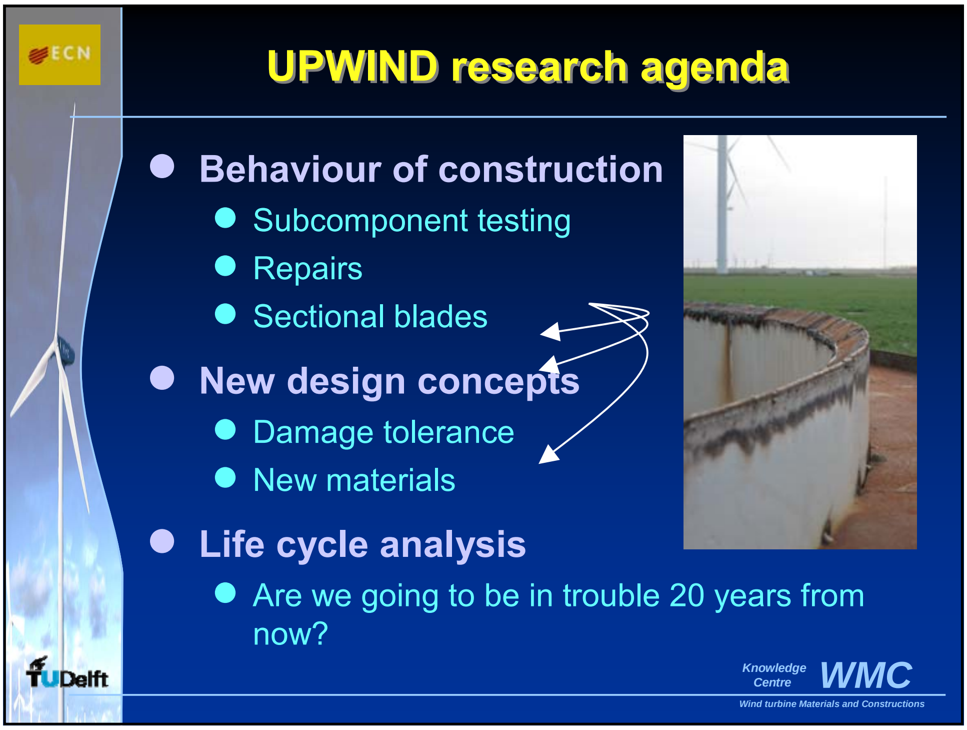
Research Agenda

- Long-term research typically in 4-5 year EU funded projects
- Focus on fatigue
- Co-operation with R&D, manufacturers and certification institutes
- Work towards guidelines
  - Improve reliability
  - Reduce design factors

Knowledge Centre WMC
Wind turbine Materials and Constructions



UPWIND WP3
Analytical Research
Experimental Research
Blade design tools
FEM models
Probabilistic approaches
Phenomenological Models
Layer-damage models
Unit cell approach
Micro-modelling
Full scale testing
(not part of WP3)
Sub component testing
Coupon testing
Fibre-testing
SEM-R&D



UPWIND research agenda
Behaviour of construction
Subcomponent testing
Repairs
Sectional blades
New design concepts
Damage tolerance
New materials
Life cycle analysis
Are we going to be in trouble 20 years from now?
TUDelft
Knowledge Centre WMC
Wind turbine Materials and Constructions

Research Agenda

- Generate model validation data
  - Reference specimen philosophy – one size fits all
  - Micro-meso-macro-sub
- Test test methods (no typo)
  - Test set-up
    - Geometry
    - Temperature/frequency
    - Fixtures

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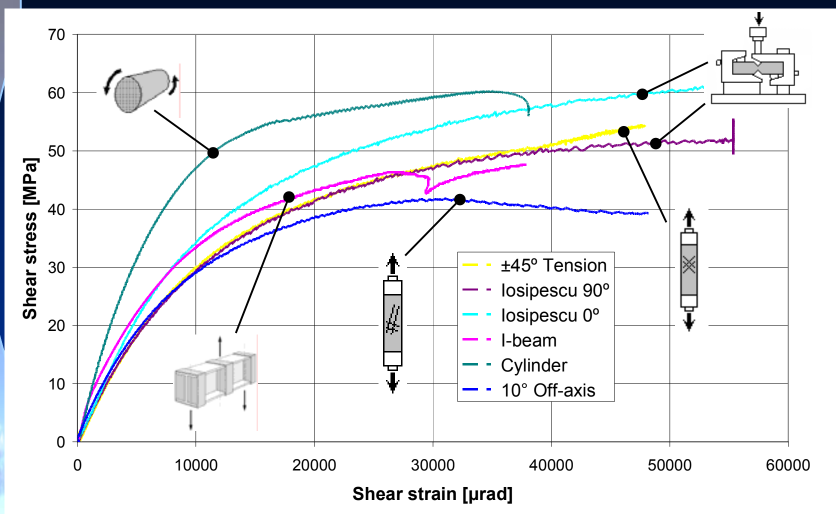
Wind turbine Materials and Constructions

Shear test comparison



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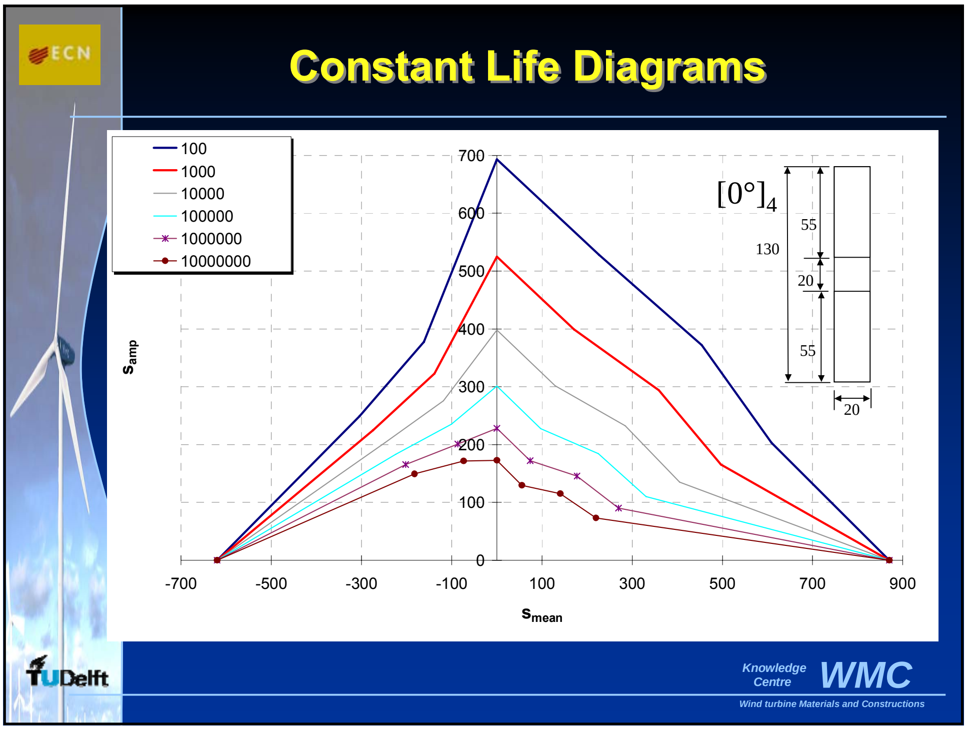
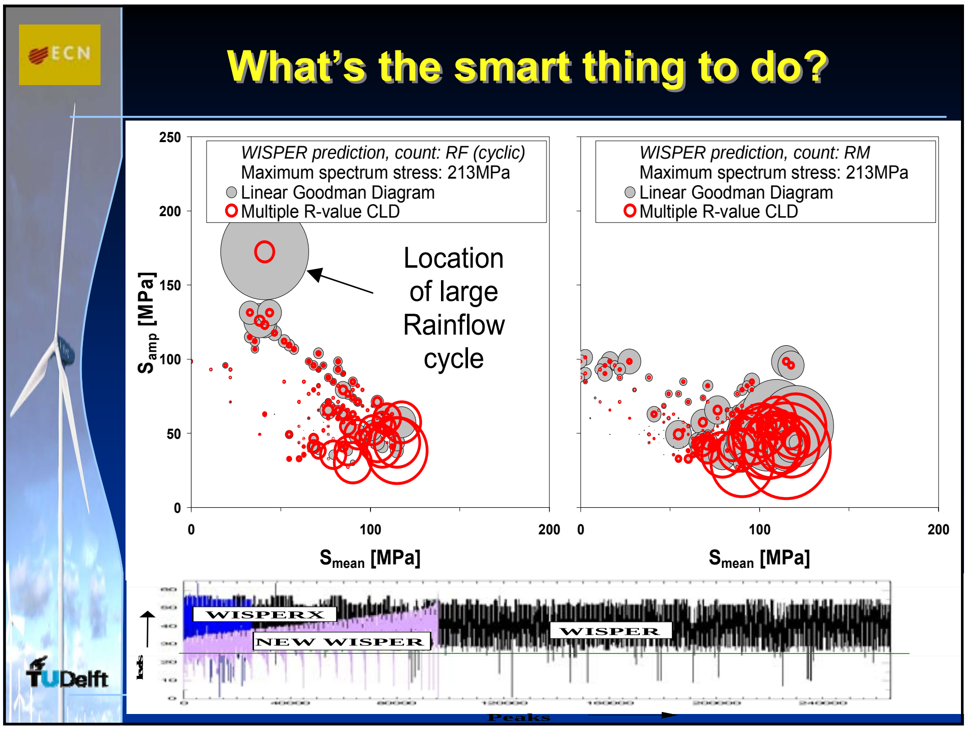

ECN
Constant Life Diagrams
100
1000
10000
100000
1000000
10000000
700
600
500
400
300
200
100
0
-700
-500
-300
-100
100
300
500
700
900
samp
smean
[0°]4
130
55
20
55
20
TU Delft
Knowledge Centre
WMC
Wind turbine Materials and Constructions


ECN
What's the smart thing to do?
WISPER prediction, count: RF (cyclic)
Maximum spectrum stress: 213MPa
Linear Goodman Diagram
Multiple R-value CLD
Location of large Rainflow cycle
WISPER prediction, count: RM
Maximum spectrum stress: 213MPa
Linear Goodman Diagram
Multiple R-value CLD
250
200
150
100
50
0
Samp [MPa]
0
100
200
Smean [MPa]
WISPERX
NEW WISPER
WISPER
Peaks
TU Delft

Condition monitoring…no smart blades without sensors?

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Wind turbine Materials and Constructions

In-house plate/specimen production

- Start monitoring during production…

Wind turbine Materials and Constructions

Condition Monitoring
EU Project AEGIS

Objectives: Application of Acoustic Emission for Condition Monitoring

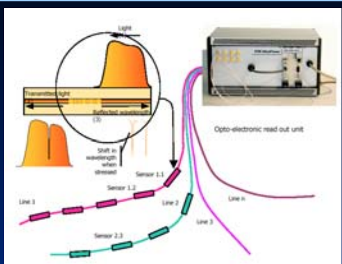
Methods Applied:
- Acoustic Emission
- Acoustic-Ultrasonic
- Fibre Optics
- Infrared Thermography.

Partners:
- WMC (NL)
- CRES (GR)
- Univ. Patras (GR)
- RAL (UK)
- Envirocoustics (FR)

PE Sensors on Blade in Test Rig

Knowledge Centre WMC
Wind turbine Materials and Constructions

Condition monitoring
NOVEM Project: Application of Optical fibres

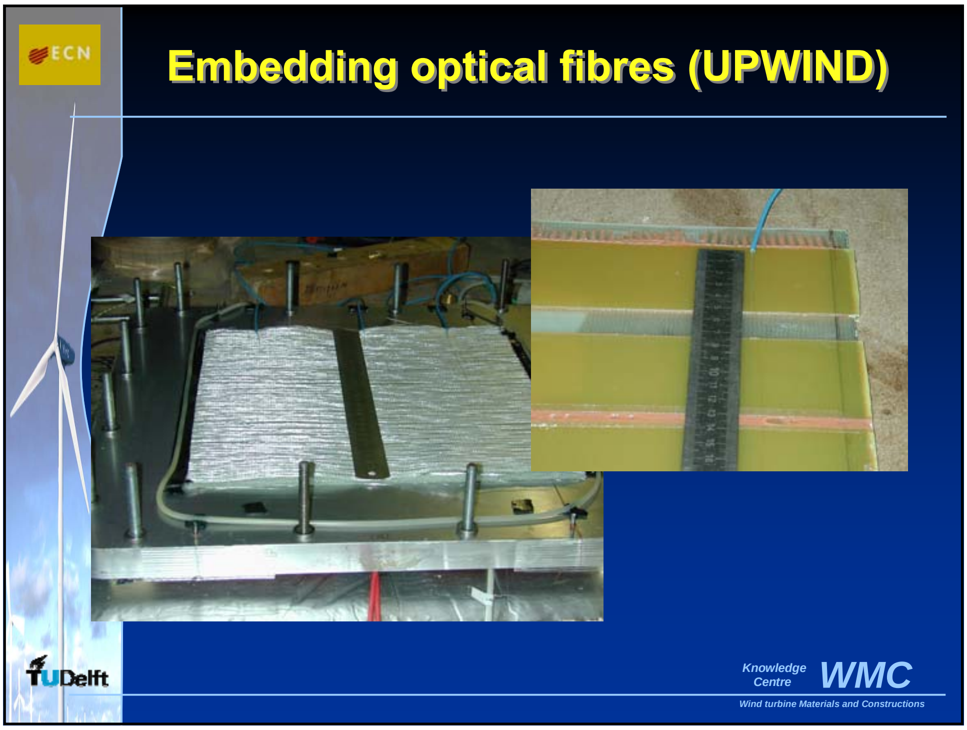


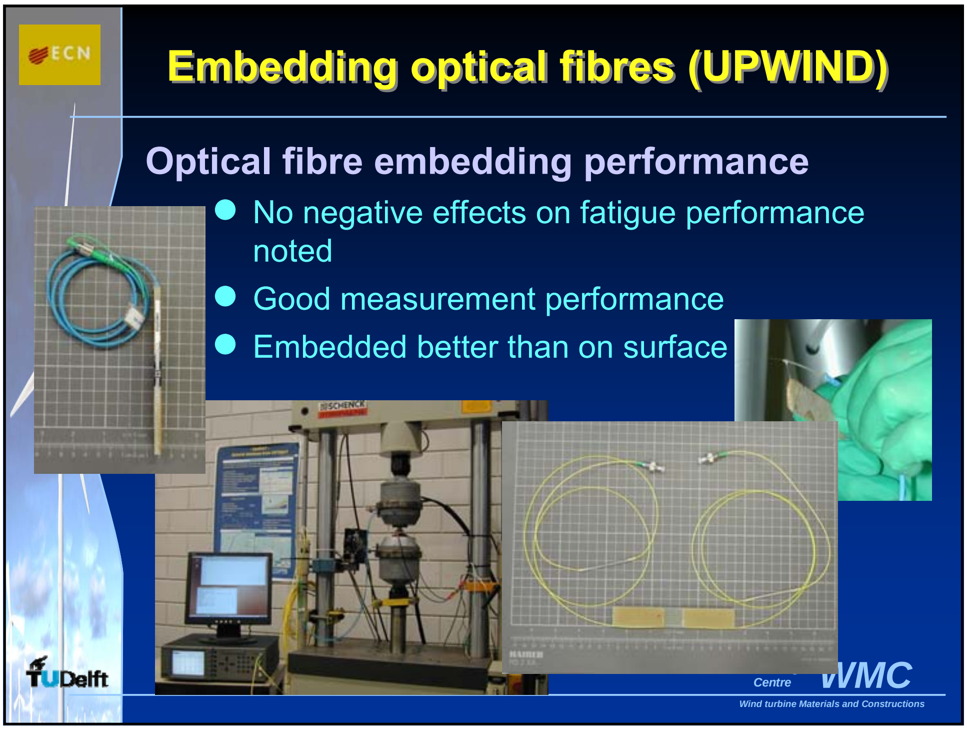
Advantages over strain gauges:
- Superior fatigue performance
- Embedded application possible
- No electrical conductance (lightning)

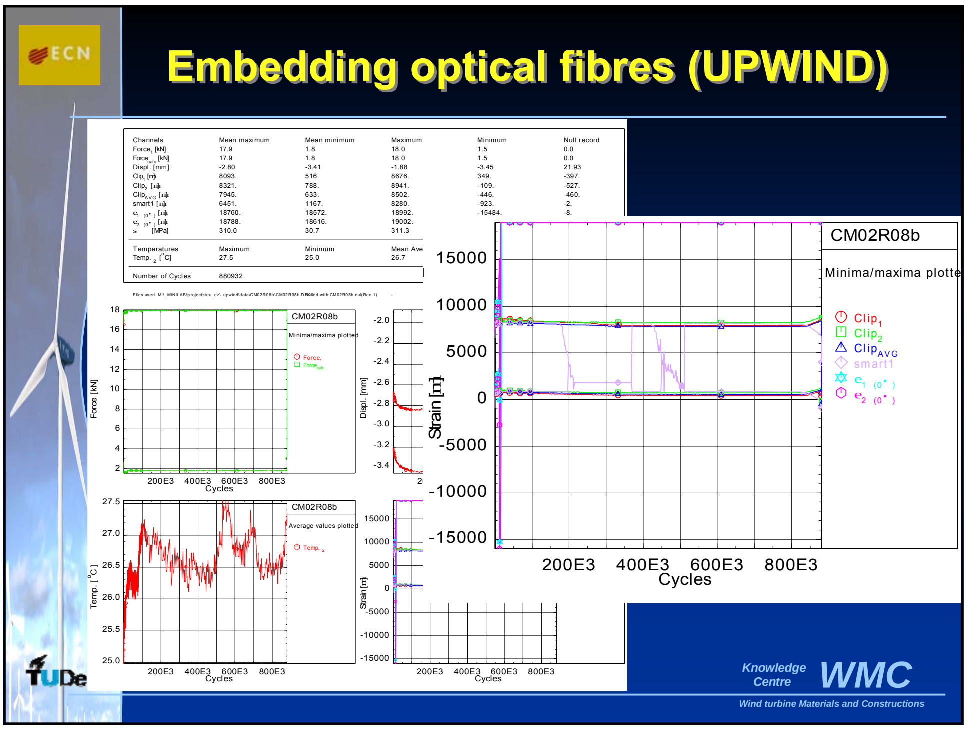
Development of practical and economical measurement system:
- Condition monitoring
- Aid for controller routines
- Measurement within thick laminates

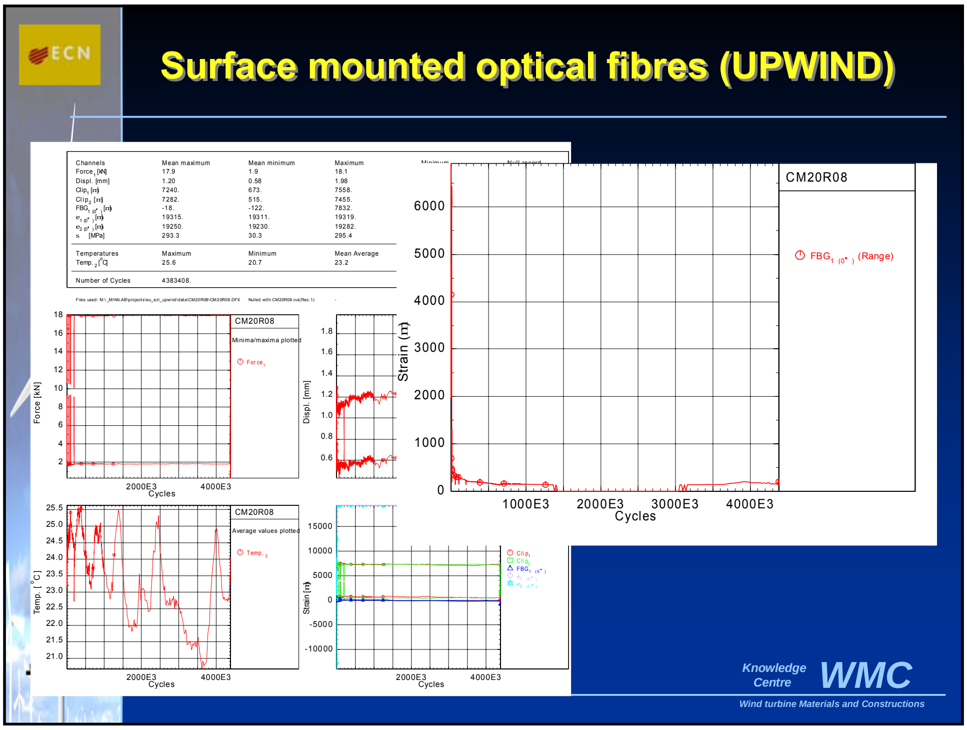
Partners:
- ECN (NL)
- WMC (NL)
- FOS consultancy (FR)
- NGUp (NL)
- Coenecoop (NL)
- NEG Micon (DE)

Knowledge Centre WMC
Wind turbine Materials and Constructions

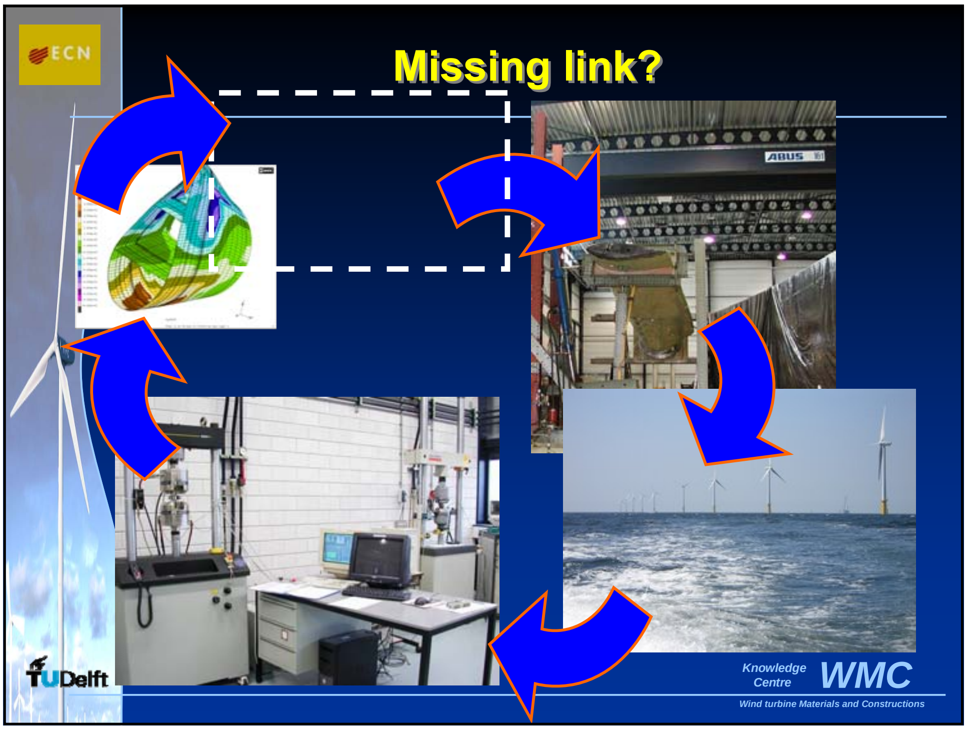

ECN
Embedding optical fibres (UPWIND)
TUDelft
Knowledge Centre
WMC
Wind turbine Materials and Constructions

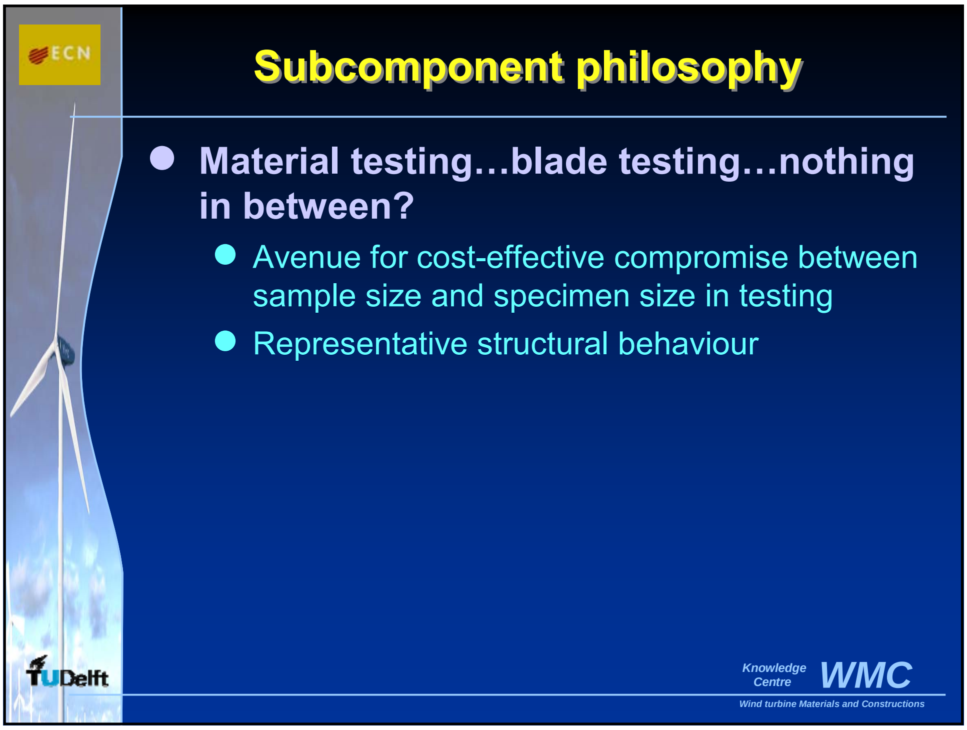

ECN
Embedding optical fibres (UPWIND)
Optical fibre embedding performance
No negative effects on fatigue performance noted
Good measurement performance
Embedded better than on surface
SCHENCK
TUDelft
Centre
WMC
Wind turbine Materials and Constructions

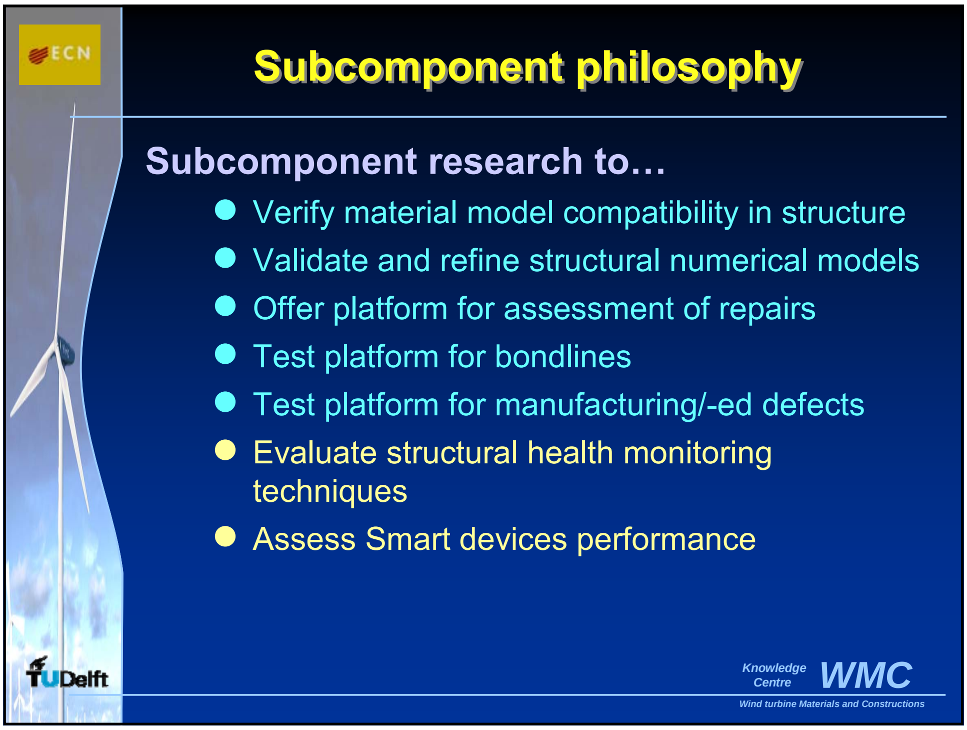

ECN
Embedding optical fibres (UPWIND)
CM02R08b
Minima/maxima plotte
Clip1
Clip2
ClipAVG
smart1
15000
10000
5000
0
-5000
-10000
-15000
Strain [m]
200E3
400E3
600E3
800E3
Cycles
Knowledge Centre
WMC
Wind turbine Materials and Constructions


ECN
Surface mounted optical fibres (UPWIND)
CM20R08
FBG1 (0°) (Range)
6000
5000
4000
3000
2000
1000
0
Strain (m)
1000E3
2000E3
3000E3
4000E3
Cycles
Knowledge Centre
WMC
Wind turbine Materials and Constructions


ECN
Subcomponents
TUDelft
Knowledge Centre WMC
Wind turbine Materials and Constructions


ECN
Missing link?
ABUS
TUDelft
Knowledge Centre WMC
Wind turbine Materials and Constructions


Subcomponent philosophy
Material testing…blade testing…nothing in between?
Avenue for cost-effective compromise between sample size and specimen size in testing
Representative structural behaviour
ECN
TUDelft
Knowledge Centre WMC
Wind turbine Materials and Constructions


Subcomponent philosophy
Subcomponent research to…
Verify material model compatibility in structure
Validate and refine structural numerical models
Offer platform for assessment of repairs
Test platform for bondlines
Test platform for manufacturing/-ed defects
Evaluate structural health monitoring techniques
Assess Smart devices performance
ECN
TUDelft
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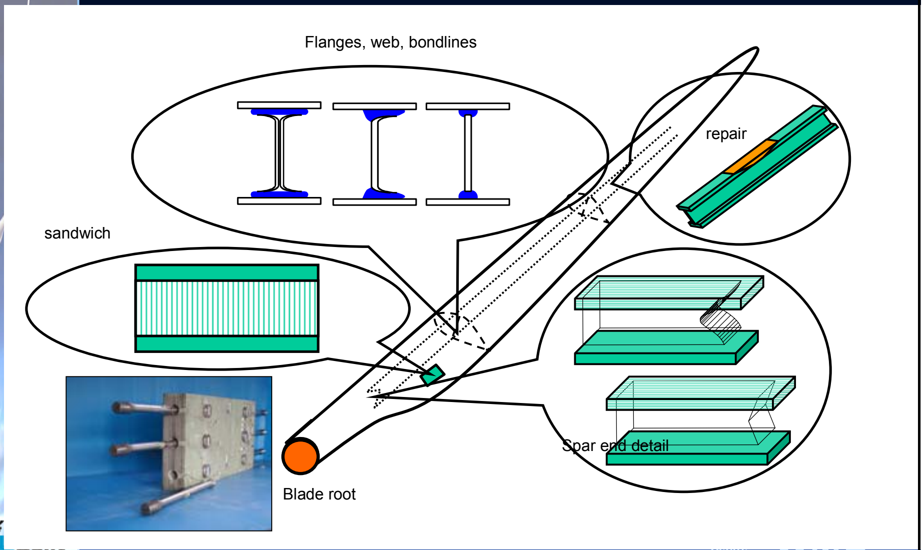
Subcomponent testing (where do we begin)



Further discussion

- Questions/comments?
- Smart devices
  - Influence on substrate
    - Connections of device to blade
    - Any holes required, e.g. synthetic jets
  - Profit in terms of fatigue life
    - Omission
    - Truncation
    - Accurate fatigue models required
  - …with respect to
    - Collective pitch
    - Individual pitch
    - Control algorithms…
  - Subcomponents as test beds

Thanks! Questions, comments?

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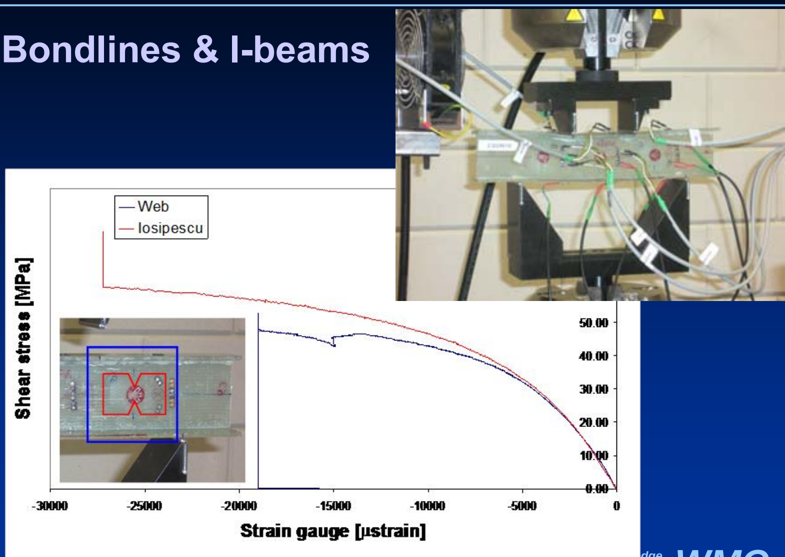
Wind turbine Materials and Constructions

Subcomponent testing

Bondlines & I-beams



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Wind turbine Materials and Constructions

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Smart Rotors for Wind Turbine Blades
- Materials and Structure -

ir. Teun Hulskamp
dr.ir. H.E.N. Bersee

Design and Production of Composite Structures
Faculty of Aerospace Engineering
Delft University of Technology

UpWind DUWIND TU Delft

Introduction

Presentation outline:

- Structural concepts for adaptive TE geometry
- Integration
- Possible active surfaces
- Conclusions

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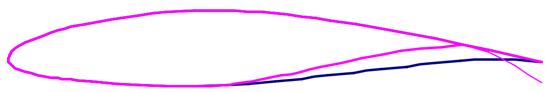
Possibilities for adaptive trailing edge

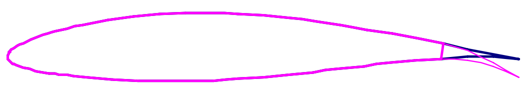
1. Reduce the chord ('chordwise compression') and add flat bender



Issues:
1. Aerofoil (re)design
2. Structurally not optimal: only same nose shape as unmodified aerofoil.

Possibilities for adaptive trailing edge

2. Reduce the chord ('truncated aerofoil') and add deformable geometry with baseline shape



Issues:
1. Larger deformable chord is needed
2. Two simple deformable surfaces will not suffice

Introduction
Adaptive TE
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Active surfaces
Conclusions

Integration

In all cases:
- Reduced lead-lag bending stiffness
- Reduced torsional stiffness

Therefore:
- Adding elements and material
- Transitions between unmodified and modified sections

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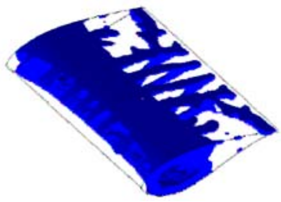
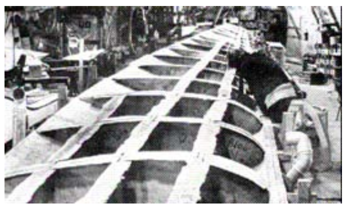
Active surfaces
Conclusions

Integration



Adding elements

Adding ribs



Rib-spar design,
in combination with **TPC material system**
Through-out the whole blade: structurally more feasible??

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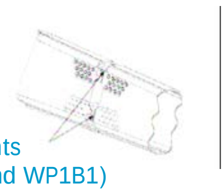
Integration

Rib-spar, TPC design through-out the whole blade: structurally more feasible?

1. (100%?) reduction in foam,
2. More easy assembling through welding,
3. Load paths,
4. Possibly added value for sectional blades.



Pin joints (UpWind WP1B1)

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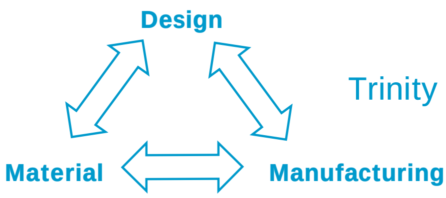
Integration

Therefore: three overlapping developments:

1. New design that becomes feasible with TPC material system
2. Create Load paths and section reinforcements for ‘reduced chord’ sections
3. Tough materials (TPs!) for deformable surfaces

Topics: HAWT blades, ‘smart’ structures & TPC



Trinity essence

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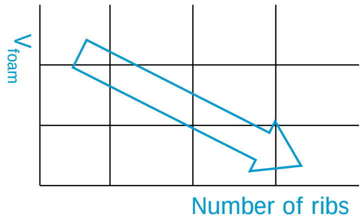
Integration

TPC redesign

Step 1. Parameter study



Constant mass,

Evaluate stiffness, stresses, critical buckling load (under aerodynamic loading and full stop)

Step 2. Rib distribution

Goal: 1. Reduce amount of foam and possibly composite material.
2. Obtain better blade

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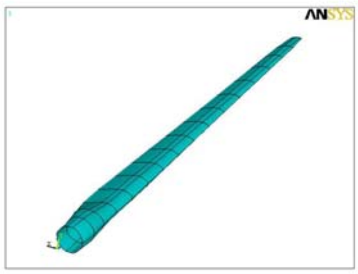
TPC redesign

Parametric blade model in Ansys.

1. **Geometry and laminate from the UpWind reference turbine blade (5MW)**
2. **Materials and ribs can be varied**

In progress, as is redesign of transition section, which is addressed separately.



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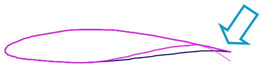
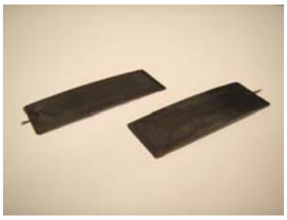
Active surfaces

Piezo-electric or SMA activated





1. **Completely different issues**
2. **SMA feasibility depending on actuation rate (1 or 3P?, the bigger the turbine, the better)**
3. **Most easily applied as flat extension**

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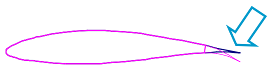
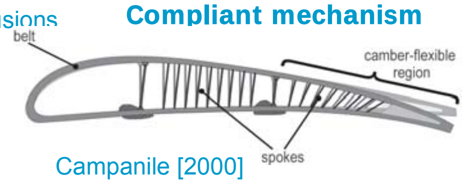
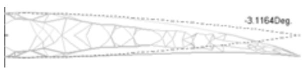
Active surfaces

Deformable trailing edge:
Compliant mechanism

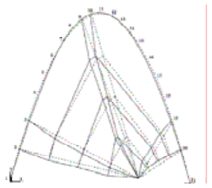




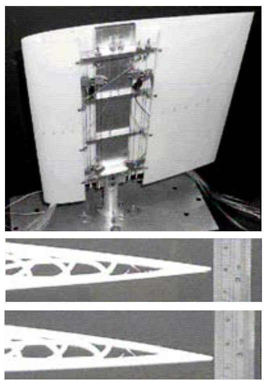
Campanile [2000]



Inthra et al. [2005]



Saggere & Kota[1999]



Strelec et al. [2003]

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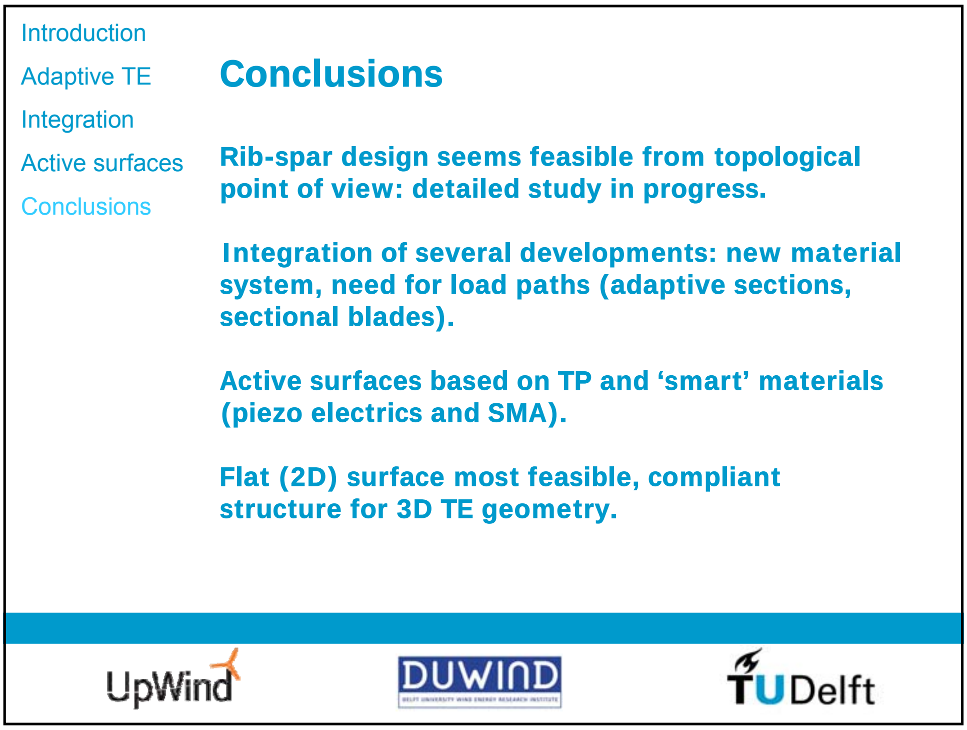
Introduction
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Conclusions
Rib-spar design seems feasible from topological point of view: detailed study in progress.
Integration of several developments: new material system, need for load paths (adaptive sections, sectional blades).
Active surfaces based on TP and 'smart' materials (piezo electrics and SMA).
Flat (2D) surface most feasible, compliant structure for 3D TE geometry.
UpWind
DUWIND
TUDelft

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UPWIND – SMA actuated adaptive airfoil

Tomi Lindroos & Merja Sippola
Jari Koskinen

Business from technology

CASE – *Adaptive wing profile*

Shape memory alloy composites

Adaptive wing profile

Modeling

Manufacturing

Control and Measurement

CASE – *Adaptive wing profile*

Background – *Shape memory alloys composites*

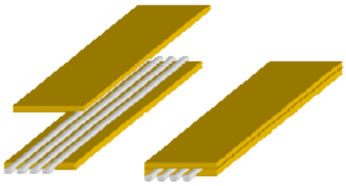
1988 Rogers *et al.* reported about composites where shape memory alloys were utilized

After that research of smart composites has been come one of the hot topics in the field of smart structures:

- More than 1700 scientific reports were published since

Three main directions of use of SMA's can be seen:

- Improve the strength of the structure against shock loads,
- Control the shape of the structure and
- Control the stiffness of the structure for vibration control.



CASE – *Adaptive wing profile*

Motivation

"Reduce loads of large wind turbine blade by replacing a part of blade with adaptive cross-section"

Founding: because of the multidisciplinary of the development work is done in group of sub-projects with national and EU funding

Main partners

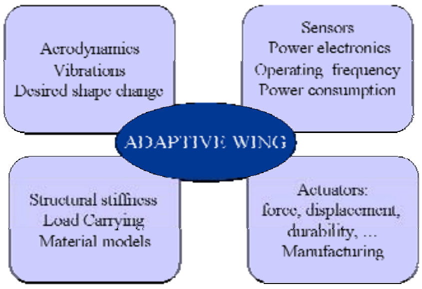
- VTT Technical Research Centre of Finland
  - Smart materials, modeling tools and manufacturing technologies for smart structures
- Helsinki University of Technology
  - Fiber optics
- University of Oulu
  - Control systems for smart structures

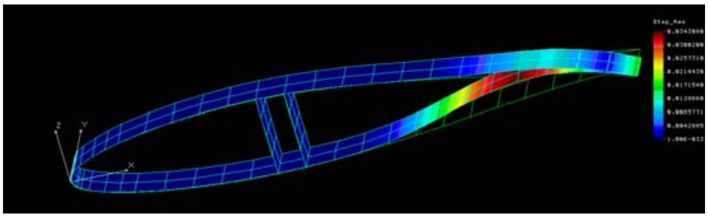
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

CASE – Adaptive airfoil

Modeling

- Structural optimization
  - Fiber angles and layers
  - Position and amount of shape memory actuators
- Material model of the shape memory alloys: implementation of Sittner's model to ABAQUS
- FE-modeling of the smart structure





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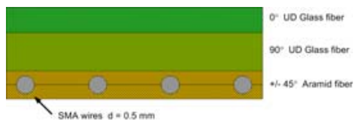
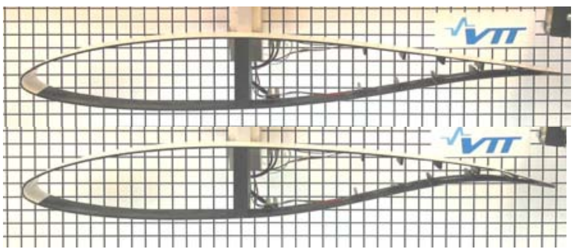
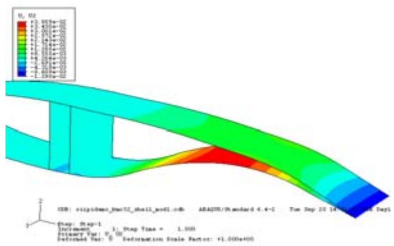
CASE – *Adaptive wing profile*

Active Wind Turbine Blade Cross Section

- SMA wires embedded inside a FRP laminate
- Controlling the trailing edge deflection
- Reducing vibration loads
- Potential in increasing energy production







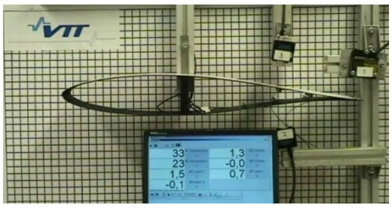
Adaptive structures co-operation between VTT, HUT and Univ. of Oulu covers the whole chain from modeling and fabrication to testing and control

CASE – *Adaptive wing profile*

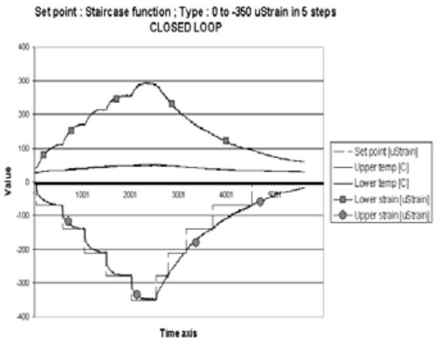
Control Systems and Measurements

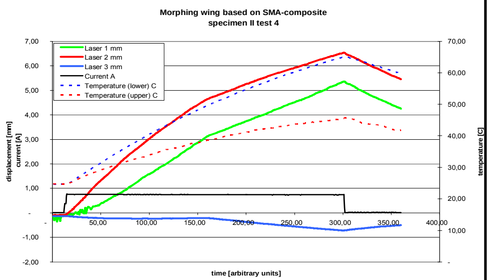
Labview based control and measurement system was developed

- Activation of SMA wires by PWM Joule heating



strain





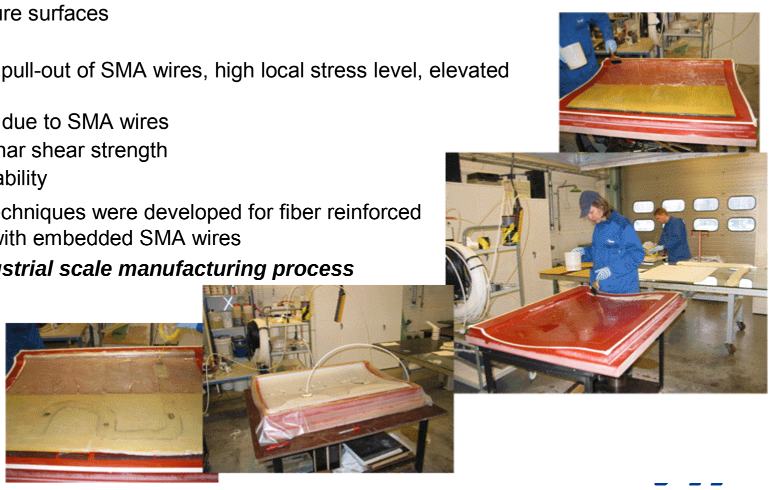
CASE – Adaptive airfoil

Development of manufacturing technologies

- Embedding SMA wires into composite structure
  - Positioning of wires
  - Double-curvature surfaces
- Structural integrity
  - How to restrict pull-out of SMA wires, high local stress level, elevated temperature
  - Discontinuities due to SMA wires
    - Interlaminar shear strength
  - Long-term durability

- New manufacturing techniques were developed for fiber reinforced polymer composites with embedded SMA wires

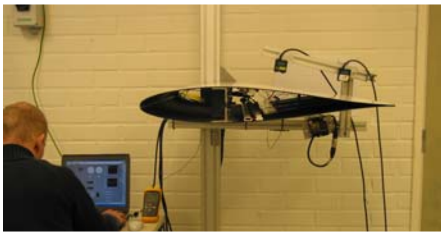
  ⇒ ***Aim: industrial scale manufacturing process***

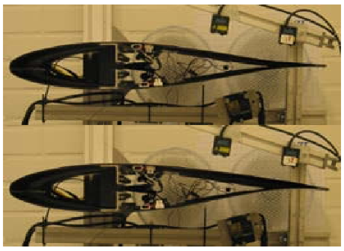


VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Preliminary testing of adaptive airfoil

- Dimensions: length 1000 mm chord 700 mm



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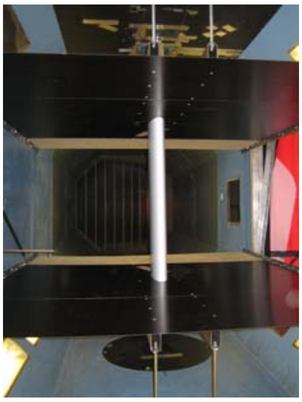
Wind tunnel test of adaptive airfoil



- Wind tunnel test of the adaptive wing profile 21.-26.9.07 at Helsinki University of Technology low speed wind tunnel
  - Test section 2m x 2m
  - Max. flow speed 60 m/s

⇒ Analyzing of the results in on-going
⇒ More detailed planning of the future actions

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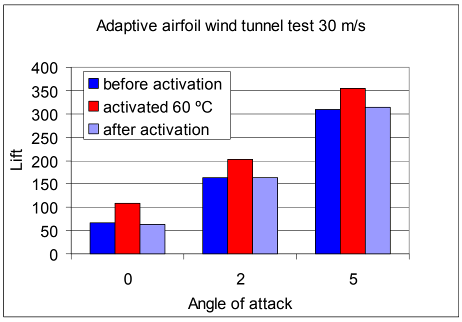
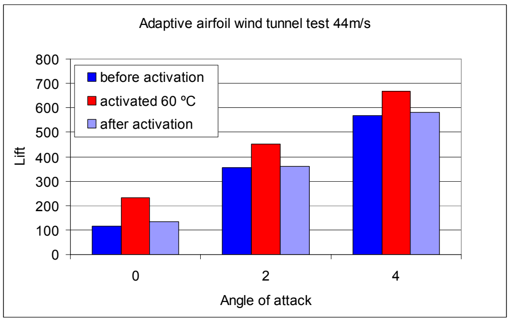
Wind tunnel test of adaptive airfoil

- Effect of activation on lift force with different wind speeds and attack angles
  - With zero attack angle lift force is approximately doubled
  - During the first activation cycles some plastic deformation can be observed





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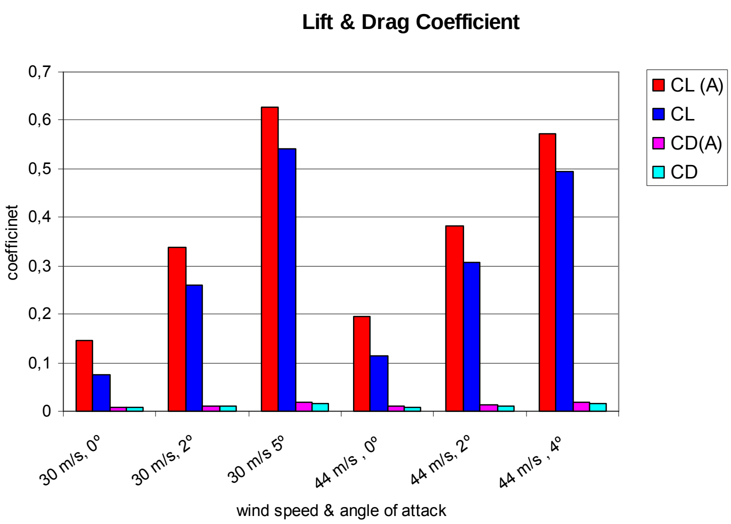
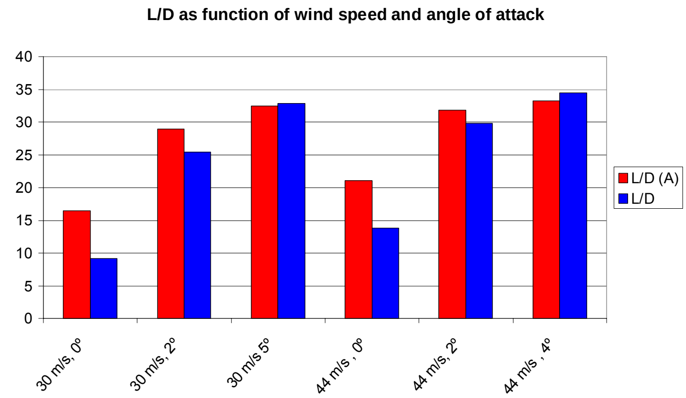
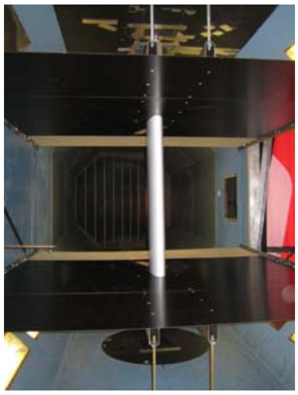
Wind tunnel test of adaptive airfoil



Behavior of adaptive airfoil



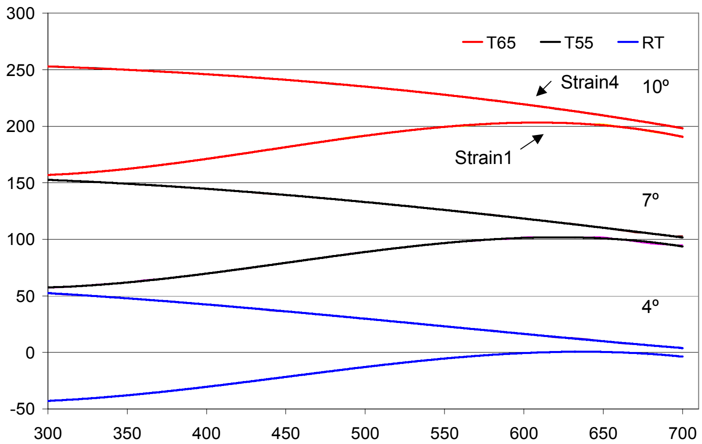


- Lift to Drag ratio (L/D) with two wind speeds and three angles of attack non-activated and activated airfoil section.
- It can be noticed that the measured L/D is considerably lower than the theoretical L/D ratio of the profile, which is about 100.
- However, the difference is well explained by the factors of the test setup.

Behavior of adaptive airfoil

- The shape and strain levels of the airfoil were determined without external stress

μstrain	T55	T60	T65
Strain1	710	1300	2060
Strain4	-840	-1060	-1160

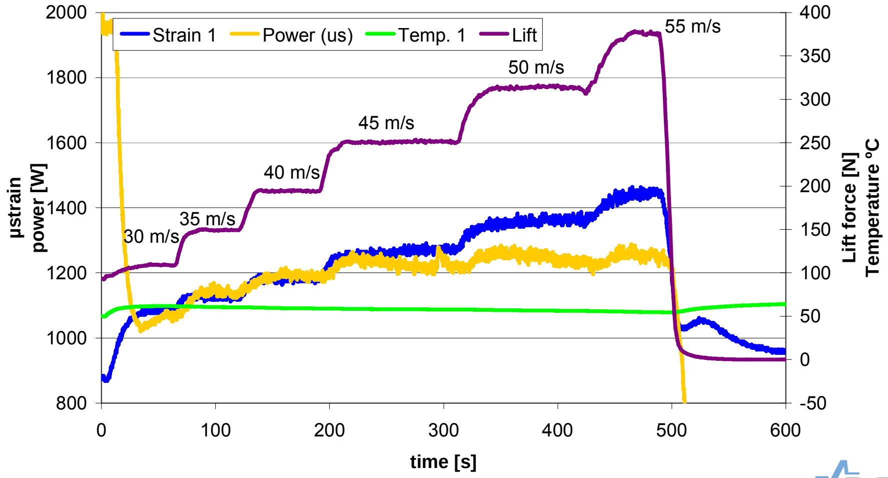


- Strain levels at 60 ºC are slightly lower than “delta strains” at wind tunnel test with 0 º and 2 º attack angles
- More detailed analysis of the strain behavior in wind tunnel test requires modeling work

Wind tunnel test of adaptive airfoil

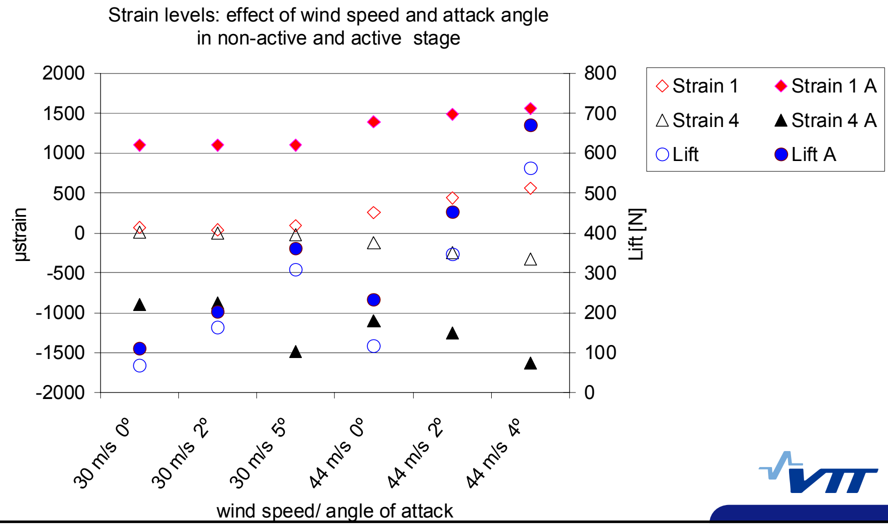
Effect of wind speed at constant activation temperature 60ºC

wind speeds: 30,35, 40, 45, 50 and 55 m/s, angle of attack º0



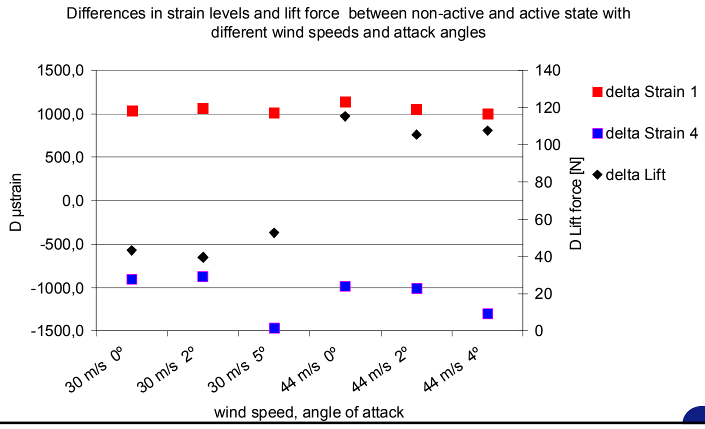
Behavior of adaptive airfoil

- The effect of wind speed and angle of attack on strain levels and lift was determined in non-active stage and active stage ~60ºC



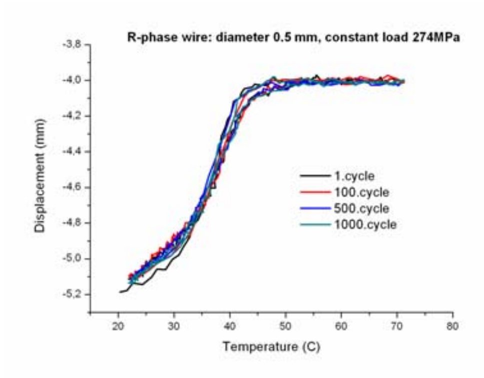
Behavior of adaptive airfoil

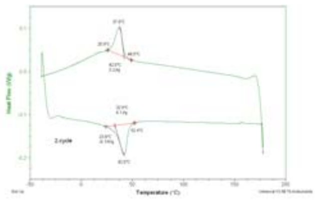
- Activation of the SMA wires causes almost equal increase of strain in lower skin (Strain 1) with all attack angles and both wind speeds.
- In the case of upper skin (Strain 4) increase of strain levels is almost constant with attack angles 0º ad 2º when increase of strain is a bit higher with higher wind speed of 44 m/s.
- The most remarkable change in strain levels at upper skin happens with higher angle of attacks.
  - In the case of wind speed of 30 m/s this change can be observed also in lift force.

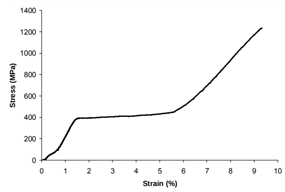


FUTURE PLANS

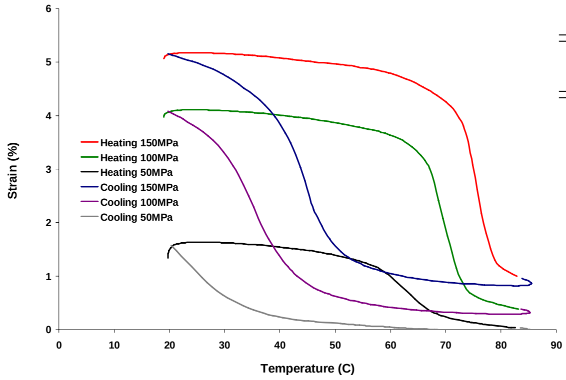
- Utilization of R-phase NiTi in SMA composites
  - Narrow hysteresis
  - Higher Clausius-Clapeyron constant gives less shift in phase transformation temperatures due to external stresses
    - ⇒ Higher actuation rate
    - ⇒ Lower temperatures
    - ⇒ Lower power consumption
    - ⇒ Lower thermal stresses to matrix
    - ⇒ Excellent resistance against functional fatigue







Thermo-mechanical behavior SMA



Memory-Metalle alloy M d = 0.49 mm

⇒ Applied stress effects strongly to transformation temperatures

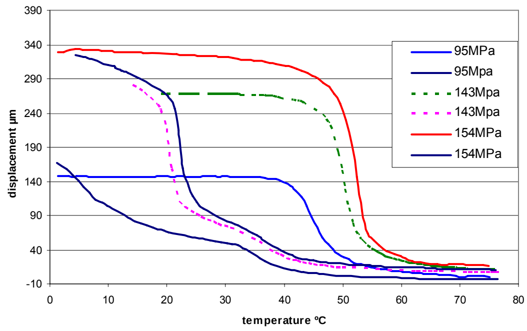
⇒ Stress of SMA wire inside the airfoil is limited below 50 MPa

⇒ Volume percent of SMA wires should be high

⇒ structural integrity

	C-C slope (MPa/C)
As	5,9
Af	10,1
Ms	4,8
Mf	4,0

Thermo-mechanical behavior SMA



Memory-Metalle alloy N d = 0.49 mm

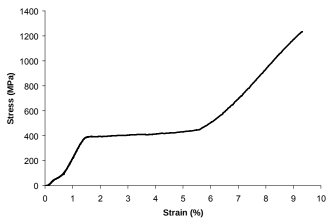
- R-phase transformation

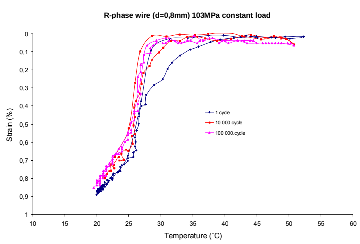
⇒ Max stress ~400MPa

⇒ Higher C-C constant

⇒ Resistance against functional fatigue

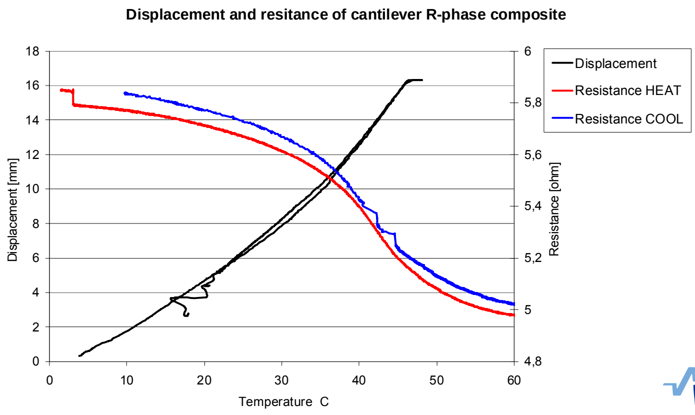
	C-C slope (MPa /C)
As	5,4
Af	9,4
Rs	18,4
Rf	12,5
Ms	4,2





R-phase SMA composite

- The very first tests of utilization of R-phase transformation in composites have been done
  - Simple cantilever beam L = 200 mm
    - ⇒R-phase actuation in composites proofed
    - ⇒Rough estimation about "reaction time" once per second (free convection)



SMA modeling

- 1D tension-compression SMA model created at ASCR is being implemented to ABAQUS at VTT, originally in Matlab, translated to Fortran at VTT
- The original model (as well as the material behavior) is stress-temperature controlled -> transformed to strain-temperature controlled by an iterative algorithm
- The model can reproduce also small loops and the restricting effect of stress on transformation -> the model is suitable for embedded actuators
- The model should work in ABAQUS before September 2008
- There exists also a Matlab version with R-phase transformations included -> this will also be implemented to ABAQUS later

Future plans

- Manufacturing of R-phase composite with larger scale
  - Step 1 laminate with larger dimensions (max. 350mm x 350 mm, work area of heating plates in hydraulic press)
  - Step 2 adaptive trailing edge based on R-phase actuation
    - Modular structure?
      - ⇒ Connection of adaptive part to the host structure

2008 IEA Expert Meeting #56

Smart Structures

Sensor Projects at Sandia National Laboratories

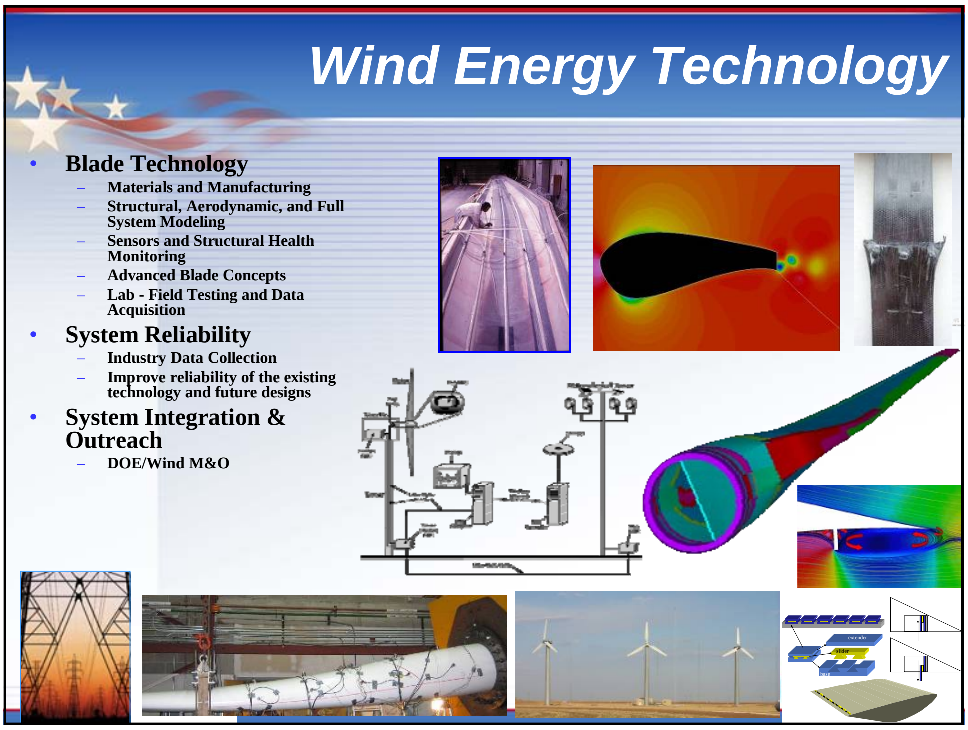
Mark A. Rumsey
Wind Energy Technology Department
Sandia National Laboratories
Albuquerque, NM

May 8-9, 2008

Presentation Outline

- **Background - Our Drivers and Opportunities for Sensors**
- **Sensor Collaborations, Partnerships and Efforts at Sandia**
- **Sensor Blade Project Overview**
- **Future Directions**
- **Topics for Discussion**
- **Questions**

2


Wind Energy Technology
Blade Technology
Materials and Manufacturing
Structural, Aerodynamic, and Full System Modeling
Sensors and Structural Health Monitoring
Advanced Blade Concepts
Lab - Field Testing and Data Acquisition
System Reliability
Industry Data Collection
Improve reliability of the existing technology and future designs
System Integration & Outreach
DOE/Wind M&O


Our Drivers for Sensors
Utilize diagnostic tools in support of Wind Energy Technology R&D
NREL/National Wind Technology Center
Boulder, Colorado
Sandia National Laboratories
Albuquerque, New Mexico
SNL and USDA-ARS
Wind Energy Test Site
Bushland, Texas
NREL
4
USDA ARS
Sandia National Laboratories

Sensing Opportunities for Everyone

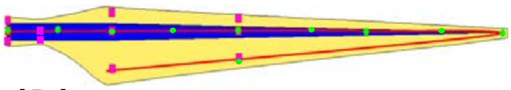
Current location of sensors on a utility size wind turbine
- Nacelle – lots
- Tower Base – lots
- Blades – **few to no sensors!**

Desire for real-time blade sensing
- Maximize structural and aero efficiency
- Advanced controls strategies
- Damage detection and Structural health monitoring
- Increase reliability and energy capture

Goal is a Smart Wind Turbine Structure

Sensor Tasks at Sandia Labs Wind Energy Technology Department

- **Fully anticipate advanced control strategies**
- **Address Sensor-in-Blade Issues**
  - **Incorporation** (material compatibility, egress/ingress, surface-mount/embed, manufacturing, maintenance accessibility, costs)
  - **Reliability** (long-term aging, robustness)
- **Sensor Blade (SBlade) Project**



- **Sensor and Active Flow/Load Control Lab**
  - **Model and validate sensor/actuation performance**
  - **Determine sensor requirements** (accuracy, reliability, cost)
  - **Evaluate various sensing technologies**
  - **Build and test subscale structures**

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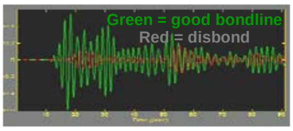
Sandia National Laboratories

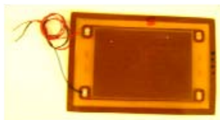
Our Sensor/Sensing Efforts

Sensor Collaborations and Partnerships:

(Foil strain gaging, modal testing and analysis, ultrasonic and acoustic emission NDT, infrared thermography, thermoelastic, fiber optic FBG, PZT/MFC sensors/actuators, photoelastic, LDV, ...)

- **Internal to Sandia:**
  - SNL Structural Dynamics Department (modal testing, NDT, SHM)
  - FAA-SNL Airworthiness Assurance NDI Center (NDT)
  - MEMS (photonics, sensors)
- **External to Sandia:**
  - NREL/NWTC (laboratory testing)
  - USDA-ARS (field testing)
  - Montana State University (composites, coupon testing, sensors)
  - Physical Acoustics Corporation (Acoustic Emission NDT)
  - North Carolina A&T (Piezoelectric Sensor Networks for Structural Health Monitoring)
  - NASA/Kennedy Space Center (Piezoceramic Transducers (MFC) /Actuator for Damage Detection and SHM)
  - University of California at Davis (Low-cost Fiber Optic Interrogator)
  - Los Alamos National Labs (SHM)
  - TPI Composites (Blade manufacturing)
  - Aither Engineering and Micron Optics (Fiber Optic FBG Sensor System for Strains, Blade Shape)
  - Purdue University (Accelerometry for Blade Shape, Load Estimation, SHM)
  - Virginia Tech (SHM)





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Sandia National Laboratories

Sensor Blade (SBlade) Project

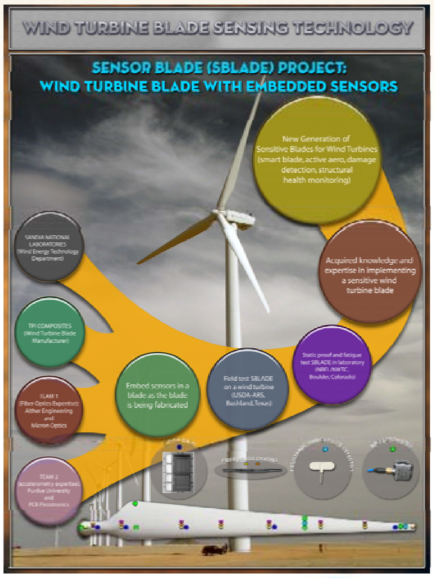
Goal: Increase the viability of wind energy by implementing sensing technologies in blades to enable advance wind turbine controls

Challenges:

- Implement sensing technologies in blades to enable advance control strategies and structural health monitoring
- * Obtain operational loads and blade shape
- * Sensor reliability, field maintenance and industry acceptance

Opportunities:

- New markets for sensing systems suppliers
- Increased wind turbine capability, reliability and availability
- Decrease the cost of energy from the wind



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Sensor Blade (SBlade) Project

- **Build a Sensor Blade** (TPI Composites, Inc., Warren, Rhode Island)
  - **Incorporate sensors in a blade during blade manufacture**
  - **Sensor list:**
    - Embedded FBG sensors (strain and temperature, blade shape)
    - Inner-surface mounted FBG sensors (strain and temperature, loads)
    - Inner-surface mounted accelerometers (blade shape, loads, SHM)
    - Metal foil strain gages (strain, loads)
    - RTD temperature
    - Streaming video on rotor (blade shape)

- **Field Test Sensor Blade** (U.S. Department of Agriculture – Agriculture Research Service, Bushland, Texas)
  - **On-the-ground checkouts and calibrations**
  - **In-the-air checkouts and calibrations**
  - **Measure loads and blade deflections during turbine operation**
  - **Real-time video monitoring**

- **Static and Fatigue Test Sensor Blade** (National Renewable Energy Laboratory / National Wind Technology Center, Boulder, Colorado)
  - **Static Proof Test**
  - **Fatigue test to SBlade failure**
  - **AE NDT, SHM (Impedance-based, Virtual Forces, Residual Force, …)**
- **Analyze datasets and report results**

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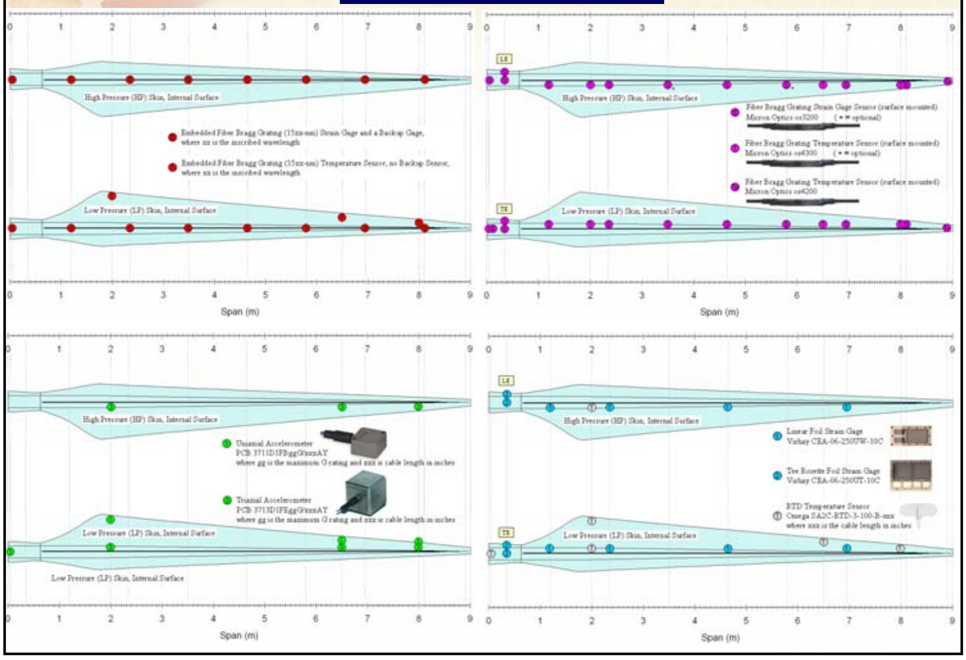
SBlade Sensor Arrays



Future Directions

- **Learn from the Sensor Blade experience**
- **“Sensor Blade 2”**
  monitor critical bond-lines, field SHM, wireless and autonomous sensors, angle of attack sensors
- **Merge sensors with advanced control strategies, and implement prototype active aero control substructures**
- **Continue looking for and evaluating new sensor/sensing technologies**

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Sandia National Laboratories

Topics for Discussion

- **Sensor Topics**
  - Long-term reliability of sensing systems
  - Sensors and advanced control strategies
  - Angle of Attack sensors
- **Quantify the impact of sensors - Cost of Energy**

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Sandia National Laboratories

Questions?

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Sandia National Laboratories

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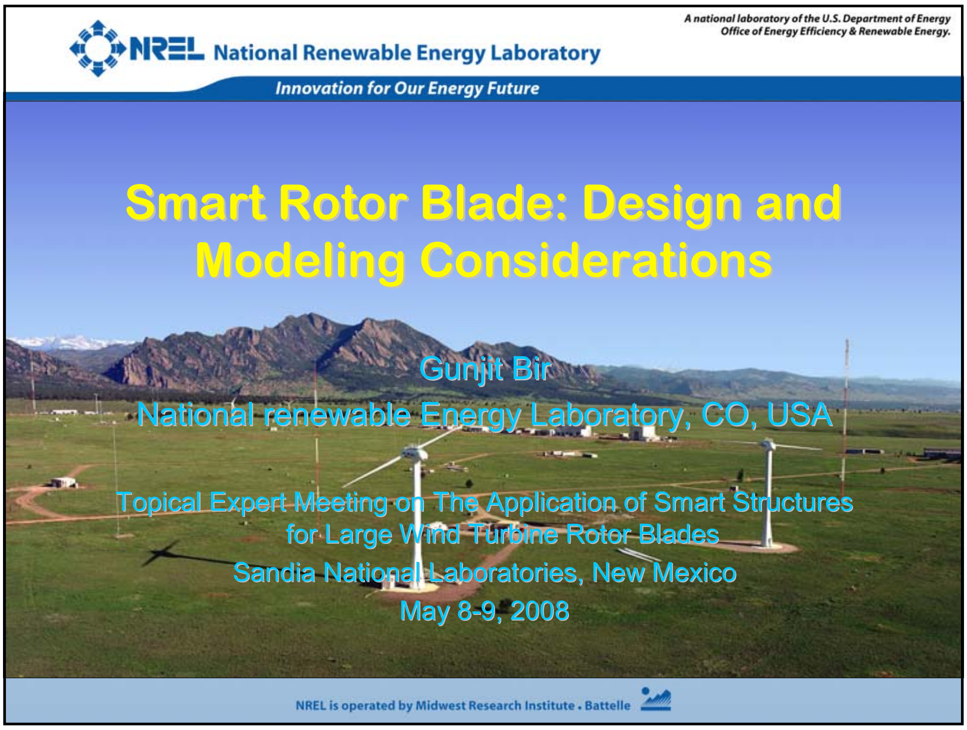


Smart Blade : Potential Benefits

- Vibration & loads reduction, transients damping
- Stability augmentation (e.g., active flutter suppression)
- Performance improvement
- Improved stability
- Noise suppression (BV interaction, acoustic and rotor/drivetrain)
- Health monitoring (automated diagnostics of impact, creep, fatigue, crack)
- Maintenance cost reduction (preventive maintenance, e.g., self-healing)

IEA Topical Experts Meeting, Dec 11-12, 2007 2 NREL National Renewable Energy Laboratory

Design Considerations

- Rotor Control:
  - Primary (Performance) Control
    (collective and cyclic control)
    Requires:
    Large amplitude, large force, and low-frequency actuation
  - HHC/IBC Control
    (vibration reduction, stability augmentation)
    Requires:
    Small stroke, small force, and moderate-to-high-frequency actuation

Primary Control Mechanisms

Best achieved using blade pitch control at the root (all-movable blade concept)

- Mechanisms:
  - Actuator tube using piezoelectric (PE) strips
  - Actuator tube using shape-memory alloy (SMA) fibers
  - Flexbeam using PE strips

  All approaches require strains outside of what smart materials can provide (in helicopter field)

HHC/IBC Control Mechanisms

- Twist (Distributed) Control:
  - Embedded PE or SMA strips
  - Embedded Interdigitated Piezo Fibre Composite
- Camber Control:
  - Embedded PE or SMA strips
  - Bi-morph bender using lead-based piezoceramics
  - Active airfoil morphing
- Movable Surface Control :
  - Leading-edge flap (primarily lift control)
  - Leading-edge flap (primarily moment control)
- Active Circulation Control

Design Criteria

Actuation concepts & active materials must

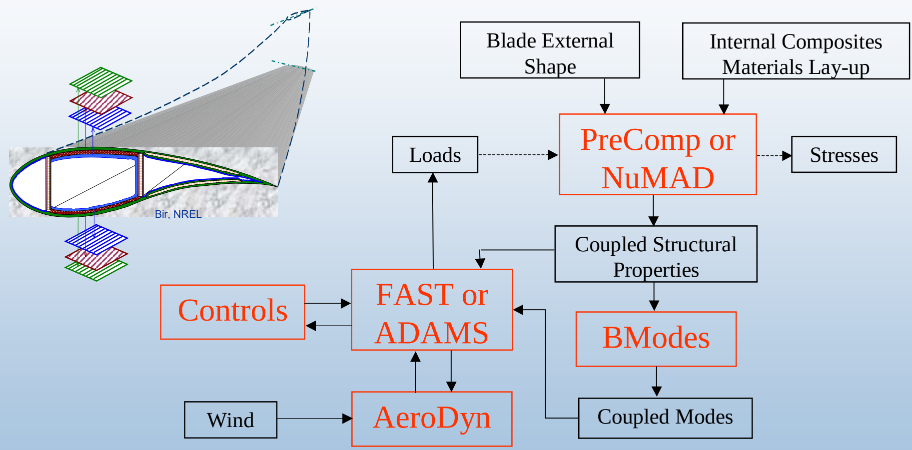
- Provide desired actuation bandwidth, forces, and stroke amplitudes
- Minimize aerodynamic drag & moment penalties
- Withstand operational environment
- Allow easy actuator/blade integration
- Maintain structural integrity (consider ply drops / interlaminar stresses)

Others: size, mass balance, dynamics, stability, reliability.

Design & Analysis Approaches

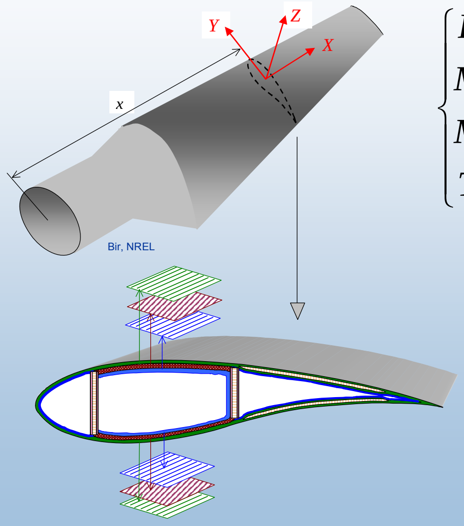
- Experimental:
  - Active materials characterization
  - Proof of Concept
  - Reliable data
    Drawbacks: questionable dynamic & aeroelastic scaling, expensive (esp. for large blades)
- Analytical:
  - Feasibility studies; assessment of alternate designs
  - Less expensive and quicker
    Drawbacks: lack of reliable materials and aerodynamic data

Current Rotor Modeling & Analysis (at NREL)

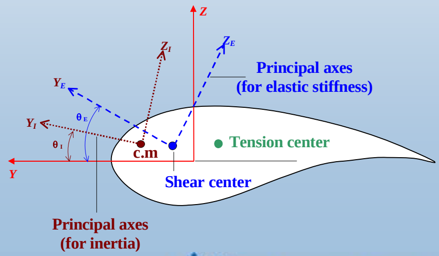


Note: Smart rotor modeling will need modification of modules shown in red

PreComp:
Blade Structural Characterization



$$\begin{Bmatrix} F_X \\ M_Y \\ M_Z \\ T_X \end{Bmatrix} = \underbrace{\begin{bmatrix} \overline{EA} & S_{af} & S_{al} & S_{at} \\ S_{af} & \overline{EI}_{flap} & S_{fl} & S_{ft} \\ S_{al} & S_{fl} & \overline{EI}_{lag} & S_{lt} \\ S_{at} & S_{ft} & S_{lt} & \overline{GJ} \end{bmatrix}}_{\text{Section stiffness matrix}} \begin{Bmatrix} u_e' \\ w'' \\ v'' \\ \theta' \end{Bmatrix}$$

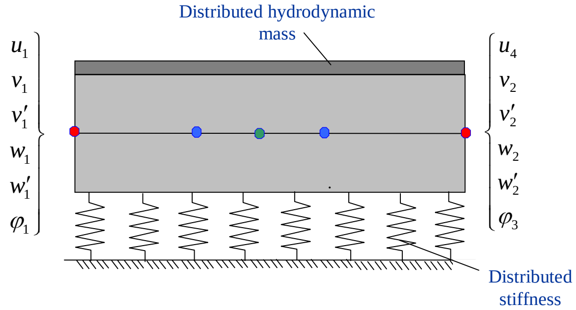


BModes

- Models a rotating blade or a tower and compute its coupled modes
- Blade allows
  - Arbitrary distribution of geometric & structural properties
  - Precone and pitch control setting
  - Tip inertia
- Tower allows
  - Arbitrary distribution of geometric & structural properties
  - Head mass and 6X6 inertia
  - Tension wires
  - Monopile support in elastic foundation
  - Floating platform (including hydrodynamic mass and stiffness)

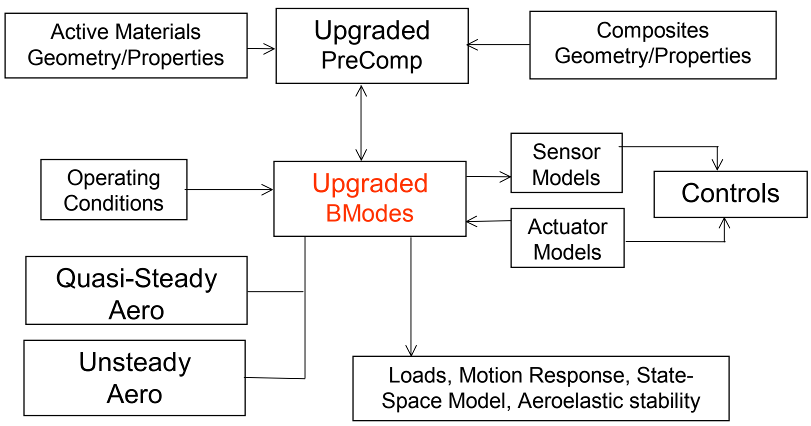
BModes (cont'd)

- Derived from UMARC
- Based on a 15-dof finite element:



- Well validated experimentally and analytically

Smart Blade Modeling & Analysis: Analytical Approach



Summary of IEA RD&D Wind – 56th Topical Expert Meeting on

THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR BLADES

May 2008, Albuquerque, USA

Background

The objective of the meeting was to report and discuss progress of R&D, in this field relatively new to wind turbine technology. The knowledge in this area has taken large steps forward compared to the situation that was presented at the previous meeting, December 2006.

Examples of this are the number of tests that was presented. Tests incorporated blade profiles equipped with movable flaps and/or micro tabs equipped with control algorithms and actuators. Hence, more integrated approach was reported, including materials, loads and control. This was an extension compared to meeting 2006 where mostly basic performances of materials and flap principles were discussed.

Participants / Presentations

The meeting was well attended with 22 participants, representing seven different countries, Denmark, Finland, Germany, Korea, Sweden, the Netherlands and the USA. The participants mainly represented research organisations.

A total of 19 presentations were given on the following topics:

1. Introductory Note - The Application of Smart Structures for Large Wind Turbine Rotor Blades

Blade and flaps

2. Latest results and future activities at Risø DTU within trailing edge flaps
3. ATEF – Feasibility study for optimising Danish upwind turbine technology
4. FOCUS Integrated design of smart structures
5. Bend Twist Coupled Blades – Redux
6. Smart rotor blade technology applied to the Upwind reference turbine
7. Variable Geometry Airfoils and Active Flow Control

Control technology, loads and sensors

8. Advanced Controls Research
9. Research Activities on Smart Sensing Technologies in Korea
10. Active Aerodynamic Blade Control Technology for Large Wind Turbines
11. On the proof of concept of a `Smart’ rotor using a traditional controller design cycle
12. Overview of Active Load Control R&D

Materials

13. Materials Research and Smart Blades
14. Smart Rotors for Wind Turbine Blades - Materials and Structure
15. UPWIND – SMA actuated adaptive airfoil
16. Sensor Projects at Sandia National Laboratories
17. Smart Rotor Blade: Design and Modelling Considerations

Wrap-up Items Discussed

At the finalizing discussion a number of different topics were handled. A general attitude was that this is a new and challenging area in the wind turbine research which in the future may result in more effective ways of controlling power production.

Below is a summary of the discussion.

1. What's new compared to Dec 2006?

- It still feels like it is a new topic. Everybody was surprised at the development and is talking about the next test. We are looking forward to what will happen in the 1-2 year timeframe when the next meeting will occur.
- What was missing was the high level of brainstorming that occurred at the last meeting. We are missing input from the aerospace industry. It is worrisome in case we are duplicating efforts (e.g., the skin can be used as pressure sensor). They (aerospace) are usually in attendance at the larger international conferences. There we gain a larger perspective and get to see more technologies; here we may be missing something, but we will only know if we attend those large conferences.

  Although things are converging, it may not be quickly enough. It is easier to stick to your own area of expertise than to branch out. Some companies/research groups tend to be reluctant to fund attendance at meetings for things they are not directly working on. As such, it is important that we establish and maintain contact with those folks to ensure cross information with the aerospace industry. In order to be effective in this technology, we need to get input from other technologies as well, which requires effective communication and interaction.
- Perhaps we could sponsor a session at conferences that are not related to wind (e.g., AIAA), or host a wind related conference and invite people with aerospace smart structures expertise. We can provide them adequate lead time to develop a conference paper/abstract on how they would apply their technology to a wind application.

2. Most promising technologies

- Are SMAs less attractive today, or still attractive?
  - It seems nice that you can go down to 1HZ at least. If they could go even faster, that would be something to consider. You could also consider timing issues—like pistons in a car. Although we didn't cover all areas of smart materials (fluids, elastomers), we will see a variety of controls in the coming years.
- Which are the most promising technologies that we see in the future?
  - Reliability will make the difference and be the determining factor in the future. Possibilities are:

- Surface suction (a company is currently working this; aside from the reliability issues, you can control the drag, but not the lift).
- Rubber trailing (micro jets, MEMS)

Although this is not a topic of this meeting, it will hopefully be a continued task to address next year.

3. Research needs in the future, what do we miss (sensors, materials, control strategies, blade design issues, actuators, reliability)?

- *Sensors:* Do we have sensors that meet out needs?
  - They need to be developed and have more reliability (developed for specific application). All results show that that we have to be able to react fast. It would be great to have one sensor that could cover a range of things, but that is not feasible. They have to be for a specific application. The sensor is the weakest part of the whole technology. We should encourage continuation of the fundamental work.
- *Materials:* We don't see much blade failure today. Is blade health that big of an issue?
  - As we are taking materials out of blades, we are pushing the limit on blade health in order to save costs. However, in the future, we could see more issues/failures with blades because of this. We need to invest in keeping blades from failing rather than watching them fail.
  - Thermoplastics are promising and continue to be worked on. However, in Germany, we will have to pay for destroying thermoset turbine blades in the future—they can no longer be landfilled. As such, as are looking at recyclable blades (sectional steel blades are being developed).
- *Control Strategies:* What do we need to do in this area to be better?
  - We need to figure out if sensors are drifting/failing. There are always two issues: 1) are they available and 2) are they easy to control via actuation.
  - There is no way to operate at partial capacity, so we shut down when something goes wrong. We should be able to operate at other than full capacity or complete shut down. When the system is completely shut down, you are getting no production.
  - ***Discussion about*** partial control and whether the system can operate at a different level (percentage) of power. Regulations are driving what the turbines have to do, but they should be able to remain in operation for a short time after a problem arises.

–

- *Blade Design Issues*
  - Manufacturing is an issue. There are some serious issues (quality assurance) in the manufacturing arena vs. what you wanted in the design (e.g., blade shape). We are learning as we go and these things are just being discussed.
- *Actuator:* Do we have the actuators we need?
  - Not yet, but we need a set of requirements for what we would like to see (such as being resilient to lightening strikes). There is plenty of room for improvement and clearly more work to be done.
- *Reliability*
  - If we develop an actuator that work, we will solve the lightening problems so we should not take things off the table just because lightening can take it out. If we find something that lasts only 5 years, but is cheap and works, we should not rule it out (everyone thinks a blade should last 20 years).
  - Devices should be replaceable/repairable.
  - One issue of reliability is how much you can claim in design space if you have something that's impacting your design load. Cost of energy constraints come back to force the design without the controller preset—we can lose all of our gain
- *Cost Issues*
  - We cannot come up with accurate cost estimates at this time because that could drive the technology that we end up using. We need to find the optimal solution, then start fiddling with it.

4. Continuation (new task, more Task 11 meetings, do nothing)?

- At this time, we are not ready to undertake a well-structured, 3-year task. Such a task must be specific and cannot be as broad as "smart structures."
- We are still in the beginning phase and we will have interesting results in the timeframe before we have our next meeting. We should continue Task 11 meetings at intervals of 1-2 years.

List of participants

IEA R&D Wind Task 11, Topical Expert Meeting
Smart Structures
Sandia National Laboratories, Albuquerque, NM, U.S.A
8-9 May 2008

The following persons have registered

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